NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

CERENKOV RADIATION GENERATED BY PERIODIC
ELECTRON BUNCHES IN A FINITE AIR PATH

by

Lawrence A. Newton

December 1983

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Microwave Cerenkov radiation is measured for the case of bunched electron beams which exceed the velocity of light in a finite air path. The theoretical equation for prediction of the form of the power for Cerenkov radiation is tested experimentally for this case. Initial verification of the theory is observed.

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Cerenkov Radiation Generated by Periodic Electron Bunches in a Finite Air Path

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Microwave Cerenkov radiation is measured for the case of bunched electron beams which exceed the velocity of light in a finite air path. The theoretical equation for prediction of the form of the power for Cerenkov radiation is tested experimentally for this case. Initial verification of the theory is observed.

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I. INTRODUCTION

Since the speed of light is modified by the index of refraction in a dielectric, it is possible for relativistic electrons to have a velocity which actually exceeds that of light in the medium. In this circumstance a phenomenon known as Cerenkov radiation arises. This radiation appears in a cone, around the direction of motion of the electrons, defined by the Cerenkov angle.

$$\theta_c = \cos^{-1} (c/nv), \qquad \text{(eqn 1.1)}$$

where c is the speed of light in a vacuum, n is the index of refraction, and v is the velocity of the electrons. This radiation is analogous to acoustic shock waves in air.

F. R. Buskirk and J. R. Neighbours [Ref. 1] calculated the power of Cerenkov radiation for the case where the electrons are bunched and the dielectric medium is of finite length. The experiments described in this thesis were designed to check those theoretical calculations.

Figure 1.1 depicts the pertinent physical relationships for this situation. See Table I for definitions of the variables. The first step in the theoretical derivation was to calculate the vector potential $\underline{A}$ and the scalar potential, ϕ , at a field point $\underline{r}$ resulting from an element of charge at a location within the electron bunch. A key factor in the analysis is that the current and charge densities which appear in the expressions for the potentials are <u>periodic</u> and may be expressed as Fourier series. Therefore, the potentials themselves may also be expressed as Fourier series, with Fourier coefficients representing the frequency components.

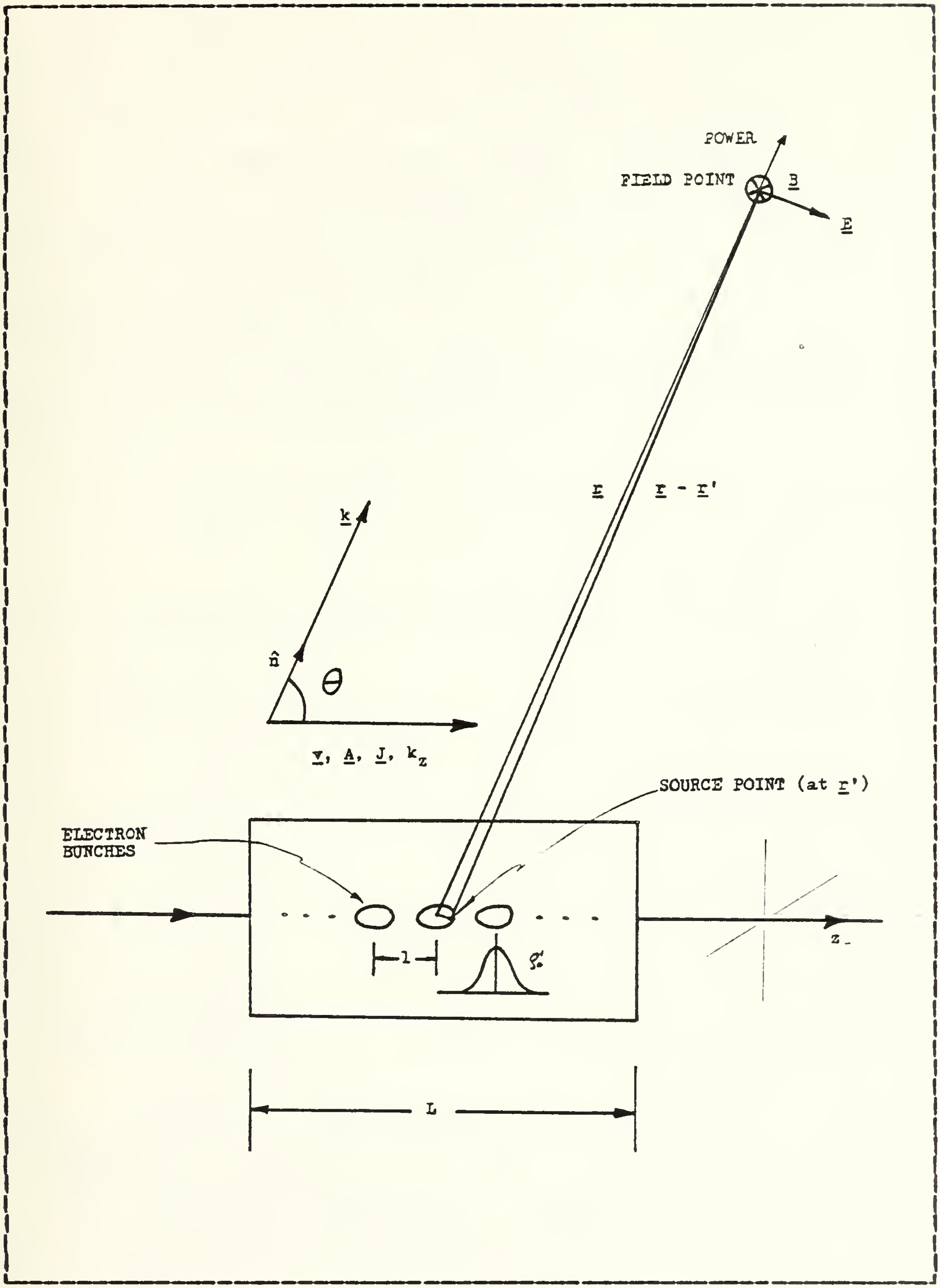

Figure 1.1 Cerenkov Radiation.

It is convenient to carry out the rest of the analysis in terms of the Fourier coefficients. The electric and magnetic field components are obtained from the potentials, and these, in turn, are used to find the frequency components of the average radiated power. An important assumption inherent in the procedure, which may directly affect experimental validity, is that the field point is assumed to be far from the source region. For details of the entire analysis, see [Ref. 2].

A principal result of [Ref. 2] is slightly recast in [Ref. 3] as the following expression for the power per unit solid angle at a given frequency,

$$W(\nu,n) = \frac{\mu}{2c} L^2 \nu^2 \nu_o^2 \sin^2\theta \, |\underset{\sim}{\rho}'_o(\underline{k})|^2 \, I^2(u) \ , \qquad \text{(eqn 1.2)}$$

with the parameters defined as follows:

$$u = \frac{kL}{2} (\cos\theta_c - \cos\theta) \ , \qquad \text{(eqn 1.3)}$$

$$I(u) = \frac{\sin u}{u} \ , \qquad \text{(eqn 1.4)}$$

and

$$\underset{\sim}{\rho}'_o(\underline{k}) = \iiint_{-\infty}^{\infty} d^3r \, e^{-i\underline{k}\cdot\underline{r}} \, \underset{\sim}{\rho}'_o(\underline{k}) \ . \qquad \text{(eqn 1.5)}$$

Refer to figure 1.1 and table I for clarification of these parameters.

The frequencies appearing in equation 1.2 are harmonics of the electron bunch frequency, which is a constant (ν_o). Thus, writing (ν) as ($j\nu_o$), and using a one-dimensional

TABLE I

Variable Definitions

$\underline{J}$	$= \rho\,\underline{v}$	=	current density
l	$= \underline{v}/\nu_0$	=	bunch spacing
ν_0		=	bunch frequency
$\underline{v}$		=	bunch velocity
$\underline{k}$		=	power propagation direction
n		=	unit vector in the $\underline{k}$ direction
L		=	length of finite emission region
$\underline{A}$		=	vector potential
$\underline{r}$		=	position vector of field point
$\underline{r}'$		=	position vector of source point
ρ_0'		=	Gaussian distribution of longitudinal bunch (charge) distribution
b		=	parameter for the charge distribution
$\underline{E}$		=	electric field vector
$\underline{B}$		=	magnetic field vector

Gaussian distribution to describe the longitudinal bunch dimension, a relatively simple Cerenkov radiation power function is given by equation 1.6 (equations 9 and 10 of **[Ref. 3]**). This is the expression which was used to compare theoretical to experimental results.

$$P_j(\theta) = \frac{2\mu\nu_o^4 q^2}{c} \frac{j^2}{4} L^2 \sin^2\theta \left(\frac{\sin u}{u}\right)^2 \operatorname{Exp}\left(\frac{-k_z^2 b^2}{2}\right), \quad \text{(eqn 1.6)}$$

Note that the radiation function varies with the square of the harmonic number, the length L of the emission region, and the angle at which the radiation is being observed. Note also the interference factor, similar to what might be experienced with optical radiation, and the way in which the bunch dimension, b, appears in the expression. The length of the emission region and the angle appear not only directly, but also through the factor u (see equation 1.3).

The results of this simple equation are quite interesting. Due to the finite size of the emission region, radiation no longer appears only at the Cerenkov angle, but throughout a range of angles determined by the (sin u)/u factor. Figure 1.2 shows how the radiation is spread for three different sizes of emission region. For a given harmonic, smaller emission regions cause greater spread, or diffraction of the radiation. The power is distributed to varying degrees among the different harmonics also, as depicted by figure 1.3. Higher harmonics have larger peak powers, and are peaked at a smaller angle than are lower harmonics.

For this experiment, the microwave portion of the spectrum was investigated, and the dielectric medium for the electron path was chosen to be air. The electrons were accelerated to relativistic velocities by the Naval Postgraduate School LINAC, which produces electrons with energies of approximately 100 Mev. For the theoretical calculations, a Fortran program (see appendix A) was used to calculate the power as a function of angle from equation 1.6. Variants of this program (appendices B and C) were used to superimpose data points over the theoretical curves.

The experimental apparatus and procedures are described in detail in the next chapter.

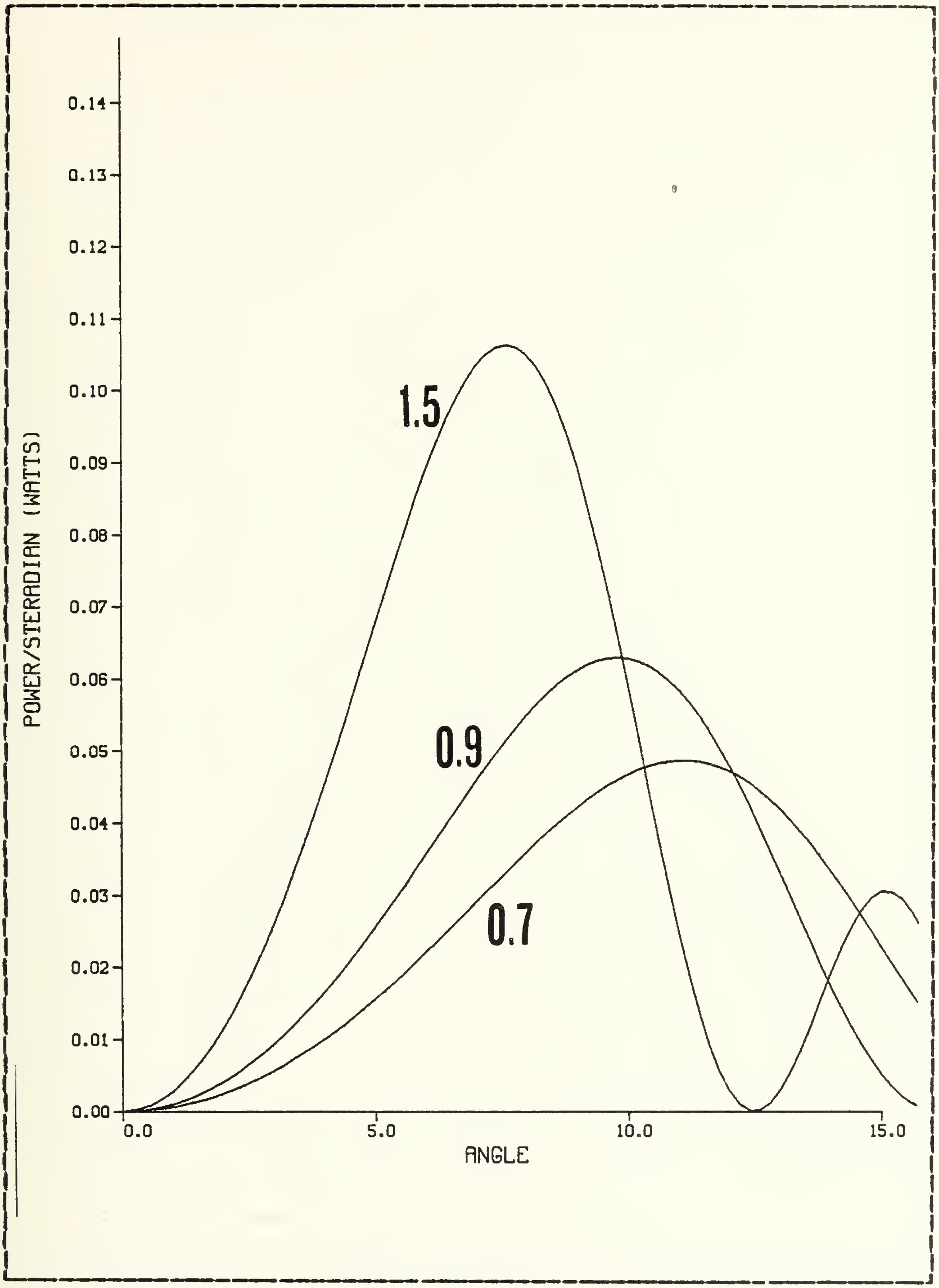

Figure 1.2 Third Harmonic for L = 0.7,0.9,1.5 meters.

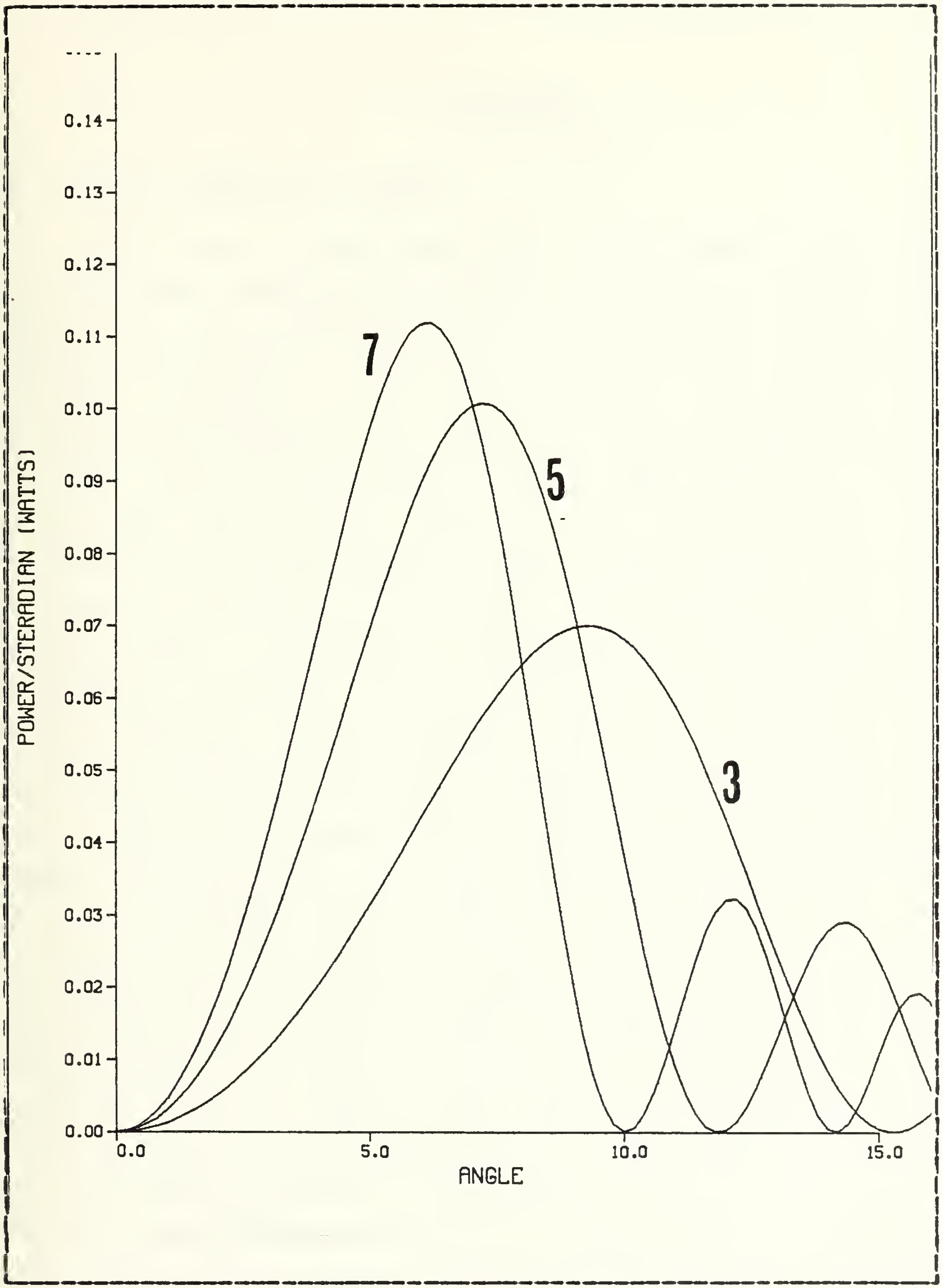

Figure 1.3 Harmonics 3,5,7 for L = 1.0 meters.

II. EXPERIMENT

A. BASIC EXPERIMENTAL DESIGN

The purpose of this experiment was to measure the power from Cerenkov radiation as a function of angle, in order to compare it with theoretical curves such as those depicted in figures 1.2 and 1.3. The basic design for this experiment is shown in figure 2.1. Photographs of the experimental apparatus are presented in Appendix D. The electron bunches exit the Linac aperture and emit Cerenkov radiation until they reach the aluminum mirror. This mirror allows the electrons to pass and proceed into the beam dump, while the microwave radiation of interest is reflected into the detector area. The mirror therefore performs the function, required by theory, that the radiation be emitted over a finite distance. The detector is mounted on a pivot arm, which is placed such that the detector is always pointed at the virtual center of the emission region. The pivot arm also fixes the distance from the center of the emission region to the detector, so that the distance over which the radiation travels is eliminated as a variable.

With this experimental setup, the basic experimental procedure was to sweep the detector over the angular range of interest using a small motor in the detector mount. The signal picked up by the detector was transmitted to the observer station, where it was fed into an amplifier and then into both an oscilloscope and a pulse height analyzer. The oscilloscope allowed a gross measure of power, while the frequency distribution measured by the pulse height analyzer gave a more precise value. The end result of this procedure was tabular data in the form of signal versus angle.

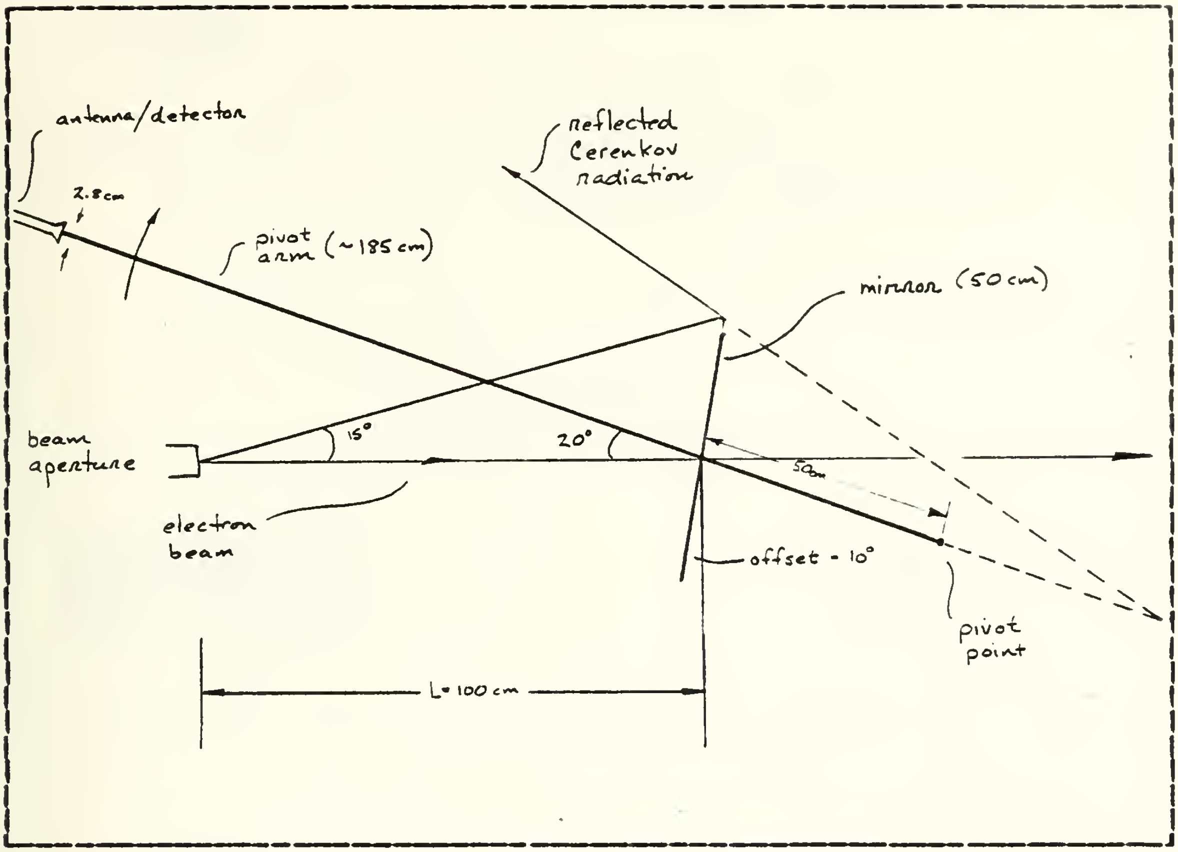

Figure 2.1 Experimental Design.

This brief overview of the experimental design is amplified in the next section with a more detailed look at various elements of the experimental apparatus.

B. EXPERIMENTAL APPARATUS

In this section, the components of the experimental apparatus will be examined, in order to provide a precise understanding of the experiment. The various components of the signal train will be reviewed in order, from the originating device itself (LINAC) to the final detection and analysis components.

1. LINAC

The salient features of the LINAC are listed in table II. These parameters are the same as those calculated by A. Saglam in prior thesis work with the LINAC at the

TABLE II

LINAC Parameters

Bunch Frequency:	2.856 GHz
Bunch Velocity:	2.997886E08 m/s
Bunch Size Parameter:	0.24 cm
Electron Energy:	100 Mev
Bunch Spacing:	10.5 cm

Naval Postgraduate School [Ref. 4]. These parameters also meet those chosen in [Ref. 3] which gives the theoretical curves for Cerenkov radiation. The LINAC provided fairly consistent signals for the experiments which are reported here. However, the signal eventually developed instabilities which precluded further experiments. That is, it became impossible to distinguish between signal variation due to the LINAC and that due to variation in the angle of detection. It may be that some of the experimental deviation from theory can be adequately explained by the variability of the LINAC itself.

2. Air Path

The air path was chosen to be 1.0 meter in length, which was convenient for the dimensions of the LINAC end station. The characteristic index of refraction for air was taken to be 1.000268, which is the same as that given for

air in [Ref. 3]. This gives a speed of light in air of 2.997127E08 meters per second, which is less than the velocity of 100 Mev electrons (see Table II).

3. Mirror

A polished aluminum mirror 50 centimeters in length was used to fix the path length. The mirror performed the dual function of allowing the electron bunches to pass and proceed into the beam dump, while causing the microwave Cerenkov radiation to be reflected into the detection area. The electron bunches continued to emit Cerenkov radiation after passing through the mirror. It was assumed that this radiation did not reach the detection area, due to the inherent weakness of the signal, and due to the distance and multiple reflections it would have to travel through in order to reach the detection area.

The mirror was tilted 10 degrees, causing the reflection axis to be offset 20 degrees from the beam axis. Therefore, the actual length of the emission region varied between approximately 95 and 105 centimeters. Measurements were made over a range of from 0 to 15 degrees. The mirror was long enough to reflect most, but not all, of the radiation at 15 degrees. See figure 2.1 for details of the geometry of the experiment.

4. End Station Detection Apparatus

The detection apparatus was mounted at the end of a pivot arm of fixed length. The pivot point was located at the center of the virtual image projected by the mirror, in order for the detector to always be pointed at the virtual center of the emission region. Theory assumed that the emission region would be a short distance, small compared to the detector distance $\underline{r}'$ (field point). Focusing the detector on the center of the emission region was done to

approximate theory as closely as possible. The pivot arm also kept the detector at a fixed distance from the (virtual) center of the emission region. Therefore, the distance of travel of the measured radiation was approximately the same for all angles, so that variation in distance would have minimal effect on the signal variation.

a. Antenna

A small antenna, with a lateral dimension of 2.8 centimeters, served as the forward end of the detection apparatus. This antenna served two functions. First, it was small enough that, with the given length of the pivot arm, the antenna subtended an arc length of approximately 1 degree. Therefore, an experimental measurement resolution of 1 degree was obtained. Further, this antenna had a very wide beam width. The antenna profiles for the electric and magnetic fields are given in figures 2.2 and 2.3. Using the half-power points as cutoffs, the beam width is found to be greater than 60 degrees for both the E and H fields, and thus for the power as well. At a distance equal to the average of that between the antenna and the mirror, approximately 130 centimeters, the beamwidth covers an arc length of 68 centimeters, which is larger than the length of the mirror.

Therefore, radiation arriving at the antenna and originating from any part of the emission region would be collected by the antenna. This again approximates the theoretical condition that the emission region be a point source, since the antenna "sees" the entire emission region at every angle of interest.

In summary, the antenna's narrow dimensions have provided spatial resolution, while its wide beamwidth has approximated a theoretical requirement.

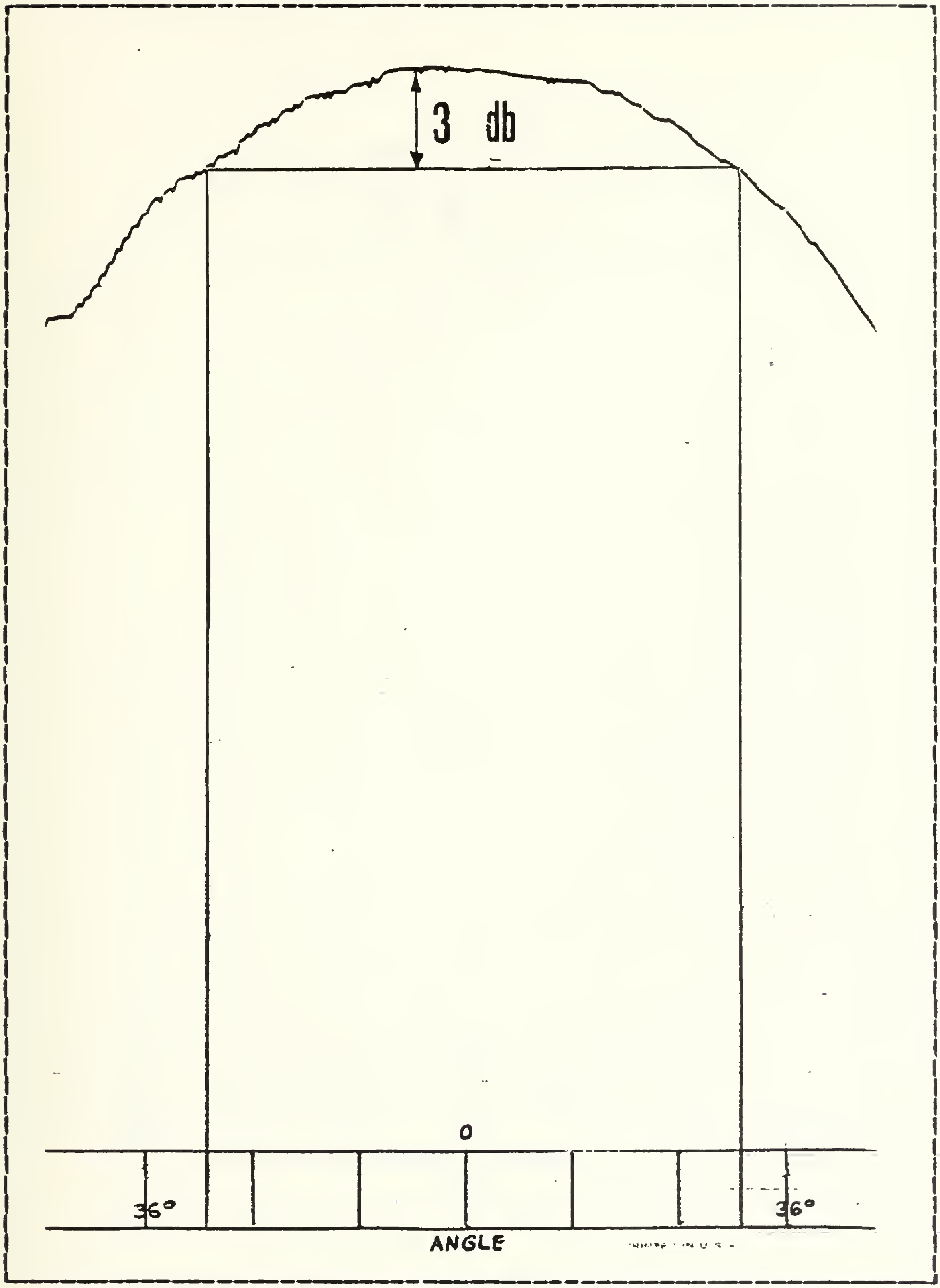

Figure 2.2 Antenna Beam Profile for the Electric Field.

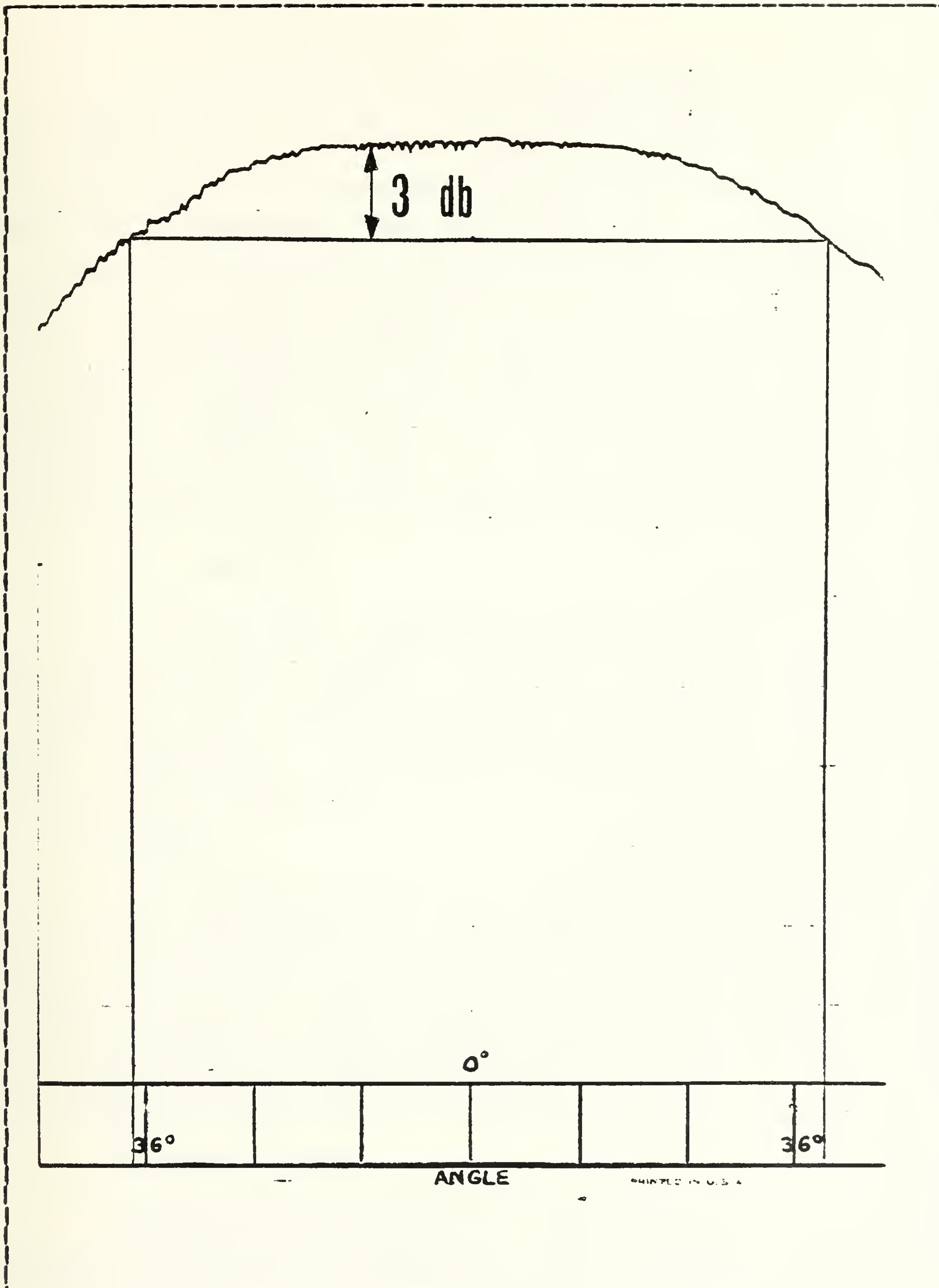

Figure 2.3 Antenna Beam Profile for the Magnetic Field.

b. Filters

In previous experiments reported in [Ref. 4] a section of X-band waveguide was included between the antenna and the crystal detector. This waveguide serves as a partial filter of the microwave radiation, since it does not pass the fundamental frequency (2.86 GHz) nor the second harmonic (5.71 GHz). Use of the X-band waveguide as a filter was included as one of the variants in this experiment. Additionally, filters were available which were able to select the third and the fourth harmonics of the bunch frequency. These filters were designed and built by K. Alexander and S. Hamel [Ref. 5]. The band-pass characteristics for these filters are shown in figures 2.4 and 2.5.

c. Detector

The final component in the detection apparatus was the detector itself, an HP X-band X424A crystal detector. The detector was used without the square-law load. Therefore, the response varied linearly with the input (Cerenkov) signal.

5. Cable

In the work done by A. Saglam [Ref. 4] the experimental area (end station of the LINAC) was described as very noisy due to the electromagnetic energy radiated by the LINAC klystrons. This problem was effectively solved in this experiment by using doubly-shielded cable to transmit the detected signal to the observer station.

6. Observer Station

The analyzing equipment consisted of an ORTEC 450 Research Amplifier, a TEKTRONIX 7904A Oscilloscope, and a TRACER NORTHERN TN-7200 Pulse Height Analyzer (PHA). The

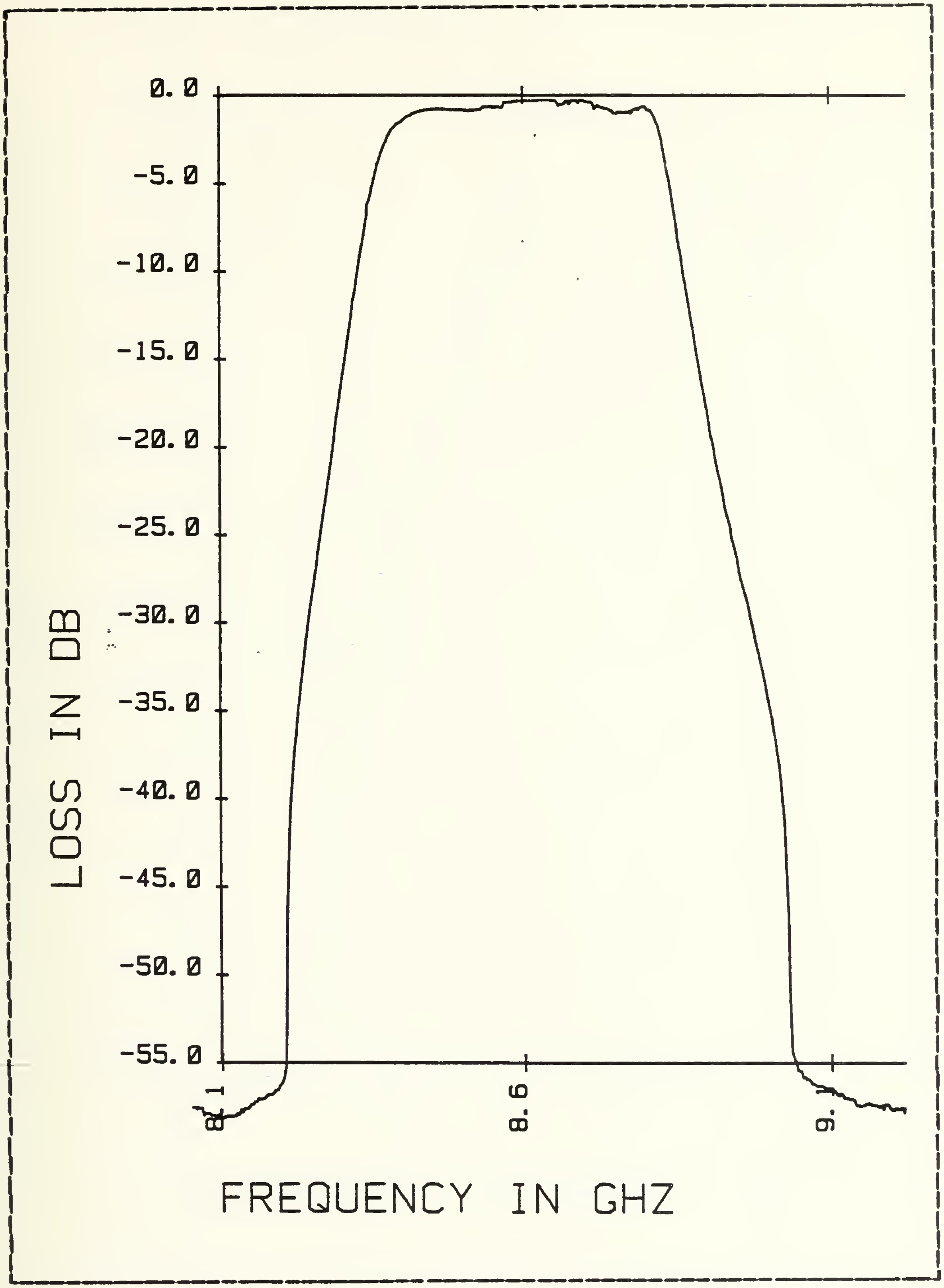

Figure 2.4 Filter Band-pass for the Third Harmonic.

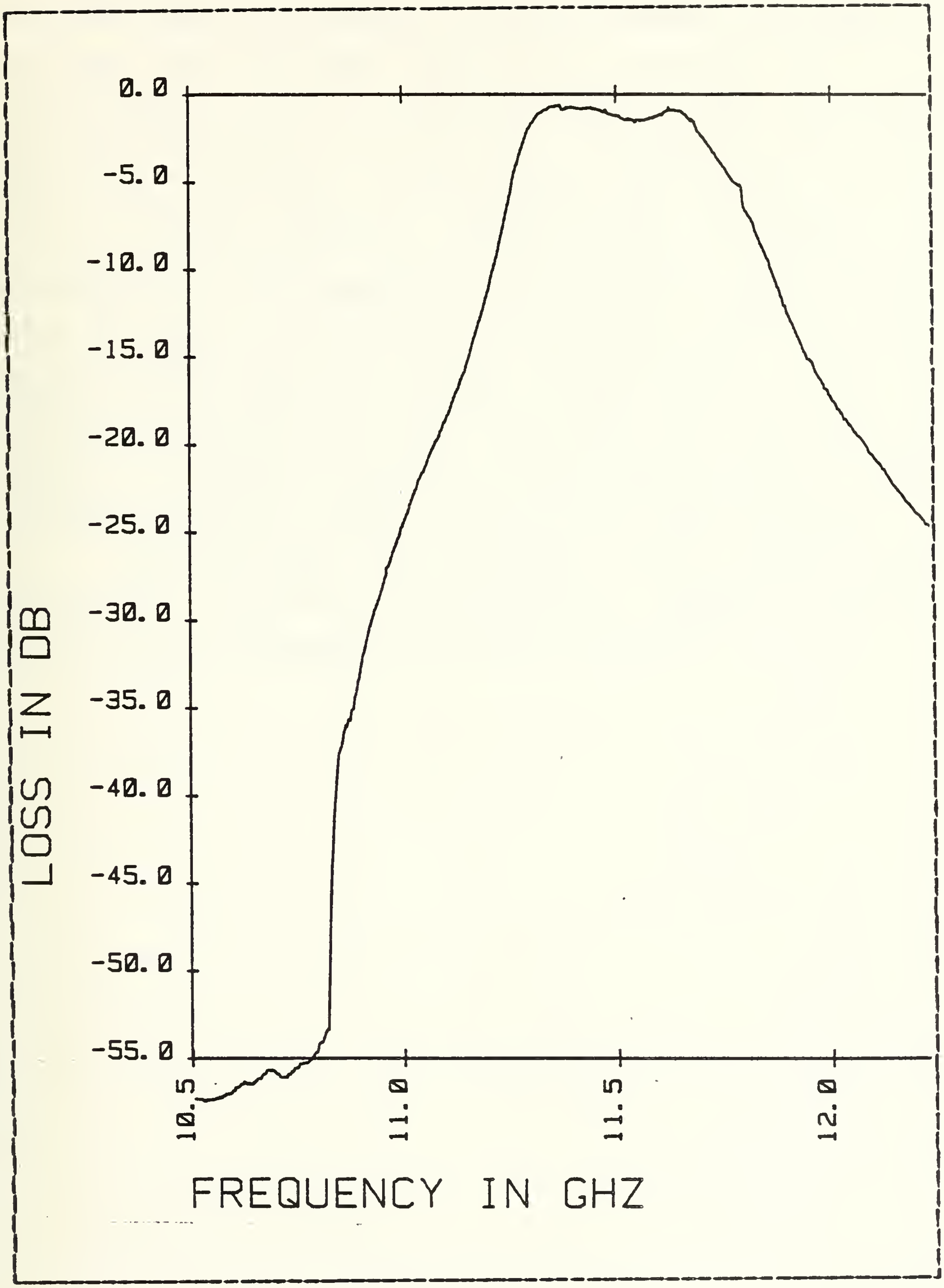

Figure 2.5 Filter Bandpass for the Fourth Harmonic.

critical piece of equipment for experimental purposes was the PHA. This instrument divided the detection range into a predetermined number of channels (e.g. 1024) and then recorded graphically the frequency with which each signal channel was detected. This allowed the observer to deal with a certain degree of variability in the signal, by choosing the observed value to be the peak of the frequency distribution. The frequency distributions observed ranged from very sharp spikes at the lower signal levels to typically broader peaks at higher signal levels. The PHA display also provided an measure of LINAC stability. If the frequency distribution of the detected signal was extremely broad or if multiple peaks were formed while detection angle remained constant, machine instabilities were indicated.

This concludes the discussion of the experimental apparatus. Comparison of experimental results to theoretical curves is presented in the next chapter.

III. RESULTS

A. METHOD OF DATA REDUCTION

As explained in Chapter 2, the raw data from the experiment was in the form of signal (power) versus angle. Since the signal was processed through a series of elements (filter, detector, amplifier, PHA), a measurement of the absolute power was not available. Therefore, it was necessary to normalize these measurements in order to make comparisons with the theoretical curves. The method of normalization chosen was the matching of peaks. For a given experiment, the experimental points were examined to determine which one had the peak value. This value was then adjusted such that it exactly matched (in magnitude) the peak value of the appropriate theoretical curve. All other experimental points for that experiment were then adjusted by the same factor, so that the experimental points maintained the same relative magnitudes.

B. DATA

The results presented here are characteristic for the experiments which were performed. Each figure shows the theoretical curve for the harmonics assumed to be present for a given filter, with the experimental points overlaid and normalized to the peak value of the theoretical curve. Tabular data for figures 3.1 through 3.5 are presented in Appendix E. Figure 3.1 and 3.2 compare the theoretical curves for harmonics three and four to the radiation measured with the appropriate filters inserted before the detector. Figure 3.3 compares the theoretical curve for the sum of harmonics three through seven with the radiation

measured with an X-band waveguide inserted before the detector.

These results appear to be good enough to indicate an initial verification of the theory. Results were best for the fourth harmonic (figure 3.2), with very close agreement between theory and experimental points. The experimental results for the third harmonic (figure 3.1) are shifted somewhat to the left of theory, while the results for the sum of harmonics (figure 3.3) are shifted to the right.

One predicted effect which is clearly evident despite the shifting is the relative spread of the Cerenkov angle for different harmonics. The third harmonic is predicted to spread the radiation over a broader range of angles than does the fourth harmonic, and this is verified by the experimental results.

There are several possible explanations for the deviations from theory which are shown here. For example, certain assumptions necessary for theoretical simplicity may not hold in the experimental situation. It may be that the charge distribution of the electron bunches is not Gaussian, or that a lateral parameter should be included in the Gaussian to account for divergence of the beam over the air path. Another factor possibly affecting the results was the mirror tilt, which caused the air path length to be longer than one meter on one side of the beam, and shorter on the other.

Another factor which must affect the results to some degree is simply the experimental geometry. For a number of reasons, theory calls for the field point distances to be much greater than the source point distances. That is, the path length should be small in relation to the distance to the point at which the fields are measured. However, the dimensions of the LINAC end station prohibit this, so that at angles larger than just a few degrees, there is ambiguity

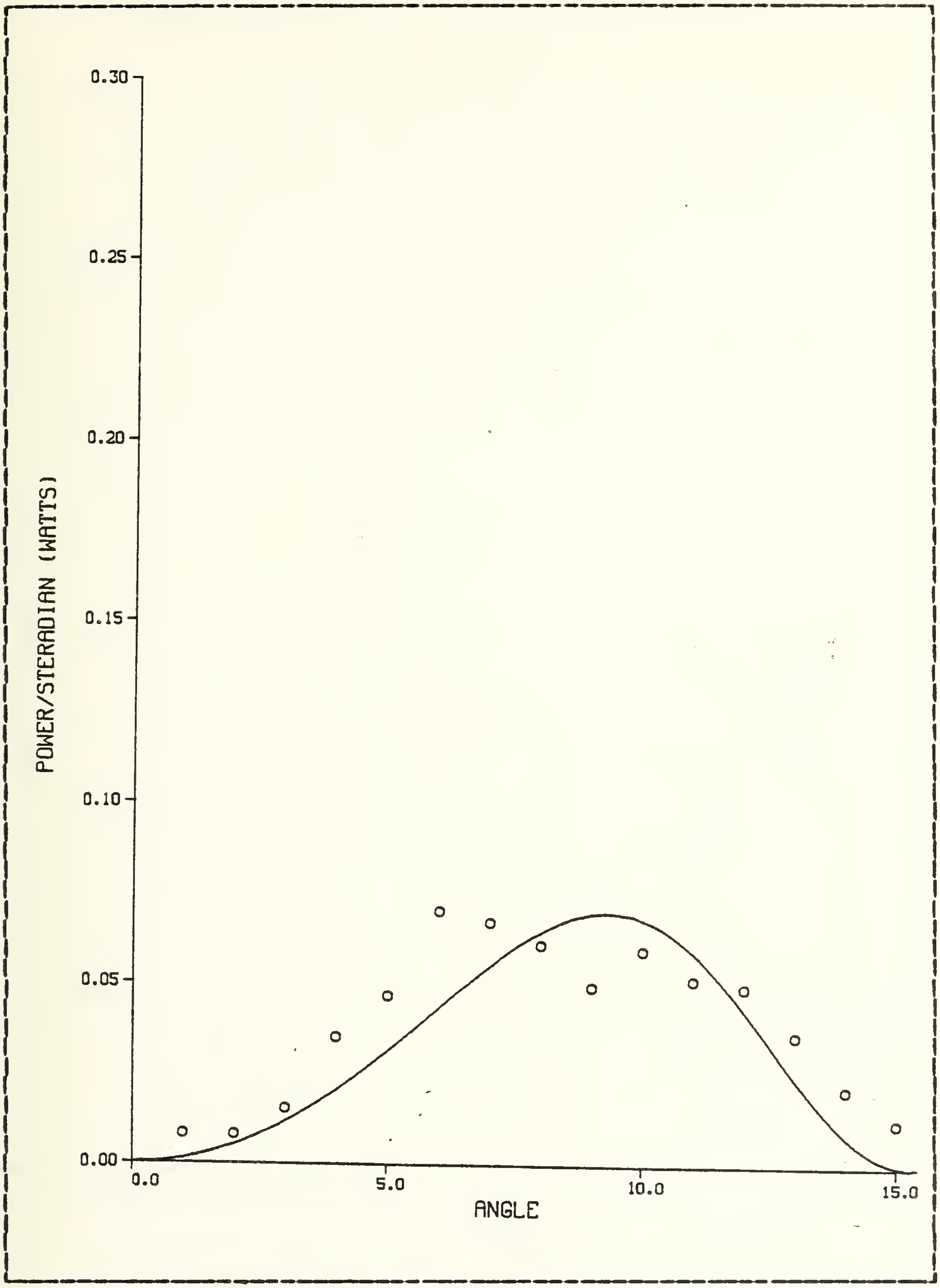

Figure 3.1 Harmonic=3 : L=1.0 m: Filter = 3rd.

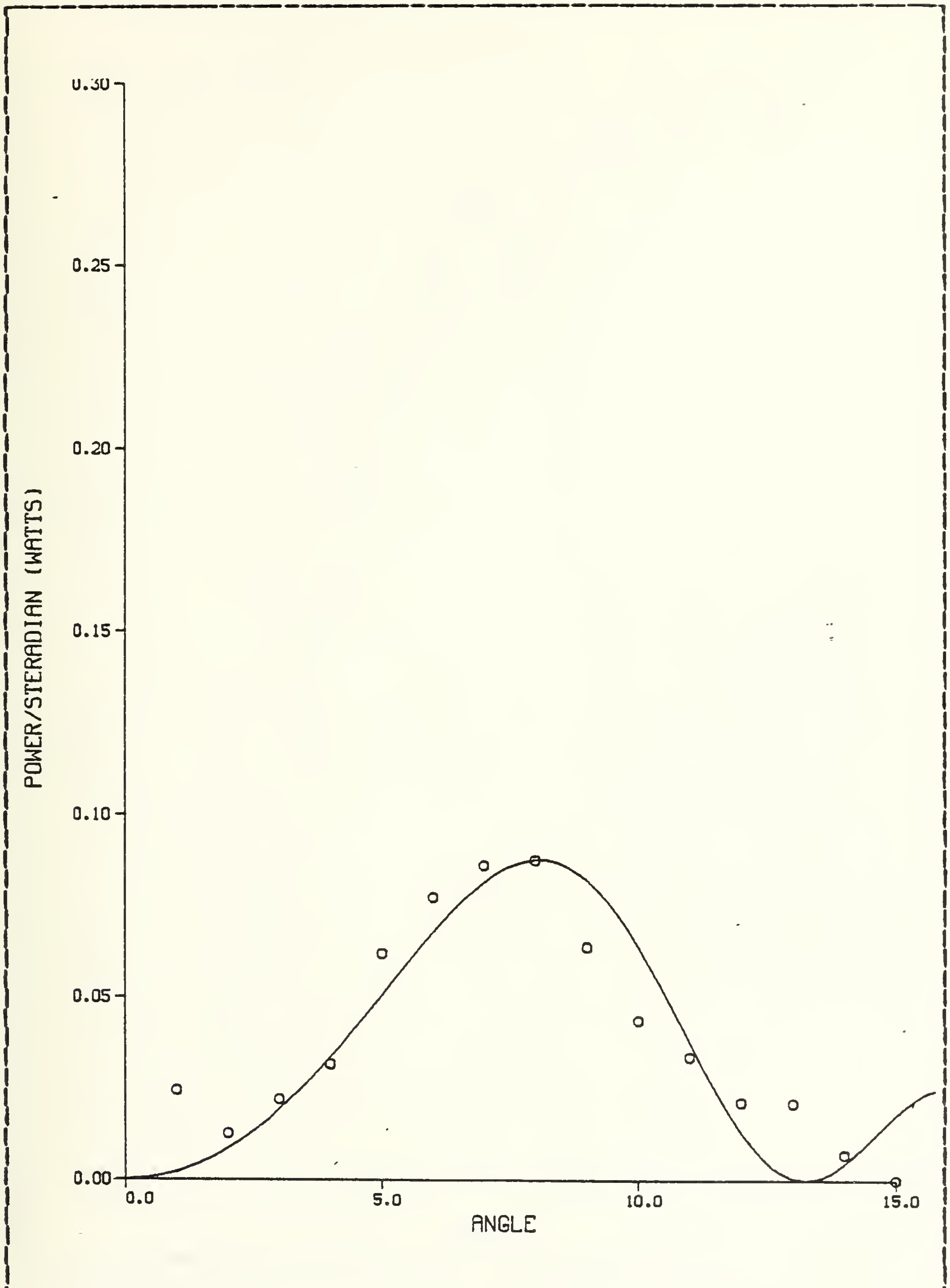

Figure 3.2 Harmonic=4 : L = 1.0 m : Filter=4th.

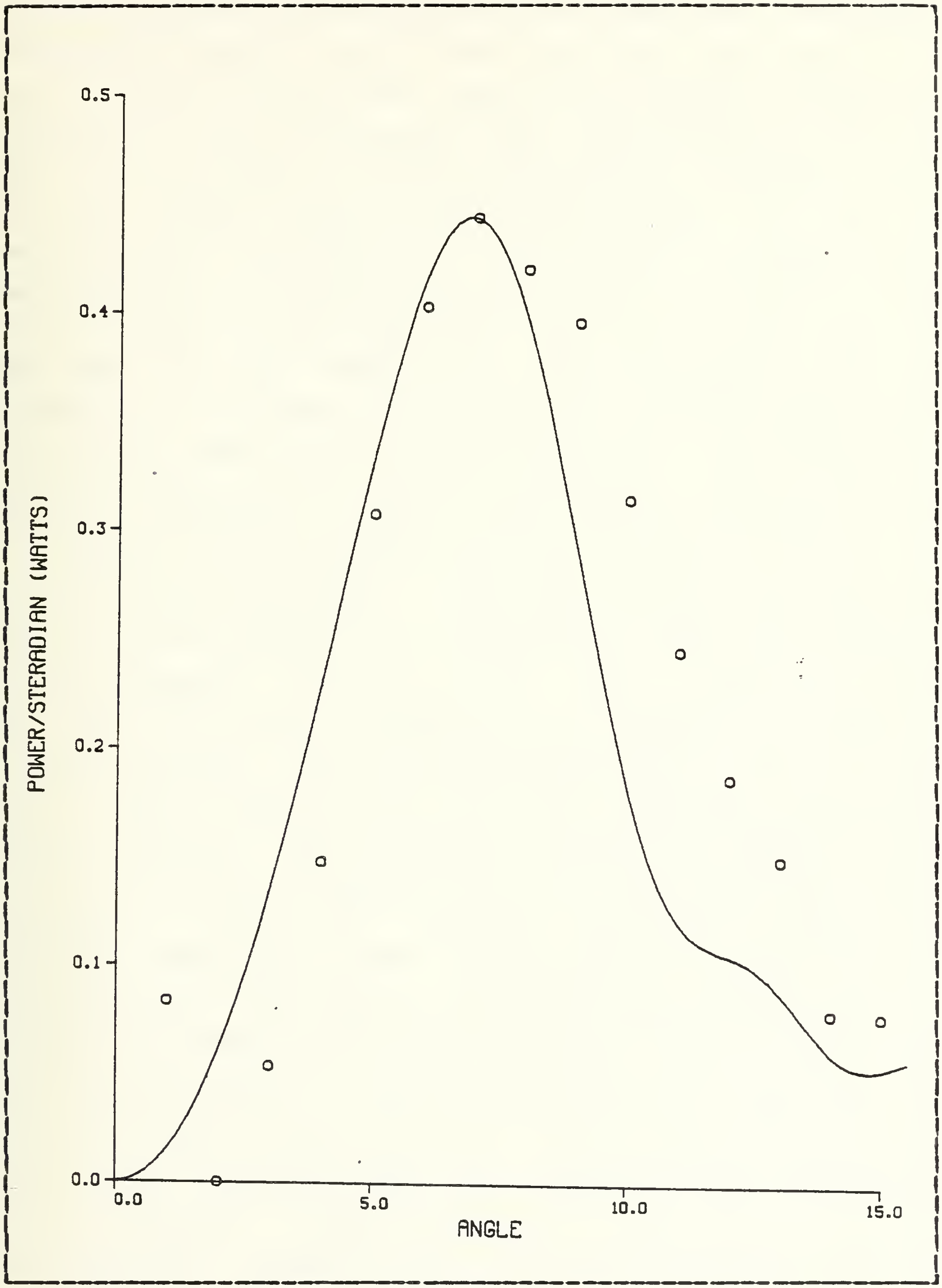

Figure 3.3 Harmonics= 3-7 : L = 1.0 m : Filter = Waveguide.

regarding exactly which angle is being measured. For small observation angles, the air path does look like a point, but as the angles become larger there are increasing differences between the angle as measured from the beginning of the air path and the angle as measured from the end of the air path. At large angles (greater than five degrees) the angle as measured from the center of the air path is substantially smaller than that measured from the end of the path. Since the radiation originating from the end of the path is stronger (it has traveled a smaller distance to the detector), and since this radiation originates at an angle larger than that which is being measured, the radiation at the measured angle is actually overstated. This may be the cause of the shift to higher angles observed in figure 3.3.

Finally, the frequency range over which the filters are valid must be considered. The X-band filters and waveguide used in this experiment are designed for use with radiation in the frequency range 8.2 to 12.4 GHz. Radiation within this band will only propagate in the dominant TE mode in X-band waveguide. Note that this encompasses only the third (8.57 GHz) and the fourth (11.42 GHz) harmonics of the LINAC bunch frequency. When radiation outside this frequency band is fed into the waveguide (as with the fifth and higher harmonics of the bunch frequency which are expected in Cerenkov radiation), modes other than the dominant may be excited in the waveguide. As indicated by [Ref. 6], the effects of coupling multiple modes into and out of a waveguide are complex, and the normal single probe configuration for detecting signal energy in the dominant mode cannot be reliably used in this situation. Since frequencies outside the X-band operating range were expected to be present in this experiment, modes higher than the dominant may have been excited, thereby causing inaccuracies in the measurement of power by the signal detector.

A comparison was made to test for the possibility that frequencies outside the X-band operating range were not being accurately measured by the single probe detector. Figure 3.3 compares the theoretical sum of harmonics 3-7 with the data measurements from the X-band waveguide, using no filter in the waveguide. Adding higher harmonics to the sum, although theoretically correct, would cause a larger discrepancy between theory and experiment, since higher harmonics are shifted towards smaller angles. Assuming the worst case, that harmonics five and above excite modes in the waveguide which are somehow not correctly coupled and detected, implies the possibility that only harmonics three and four are being measured when X-band waveguide is used as a filter. Figure 3.4, showing the data gathered with the waveguide filter normalized against the sum of harmonics three and four, appears to fit the data better, in that the width of the theoretical curve is more closely approximated by the experimental points than in figure 3.3. This lends some credence to the supposition that the detector does not respond well to harmonics higher than the fourth.

A second comparison was made to investigate the possibility that the filters which were used to isolate the third and fourth harmonics were also passing higher resonant frequencies.Such higher frequencies would be close to multiples of the frequency which the filter was designed to pass. For example, figure 3.1 compares the data gathered with the filter for the third harmonic to the theoretical curve for the third harmonic. Figure 3.5 compares the same data to the theoretical sum of the third and sixth harmonics. Note that a somewhat better fit of the data at the smaller angles is obtained in figure 3.5, indicating that the filter may be passing higher resonant frequencies, which in this case are measured by the detector, despite the effects of higher modes which may have been excited.

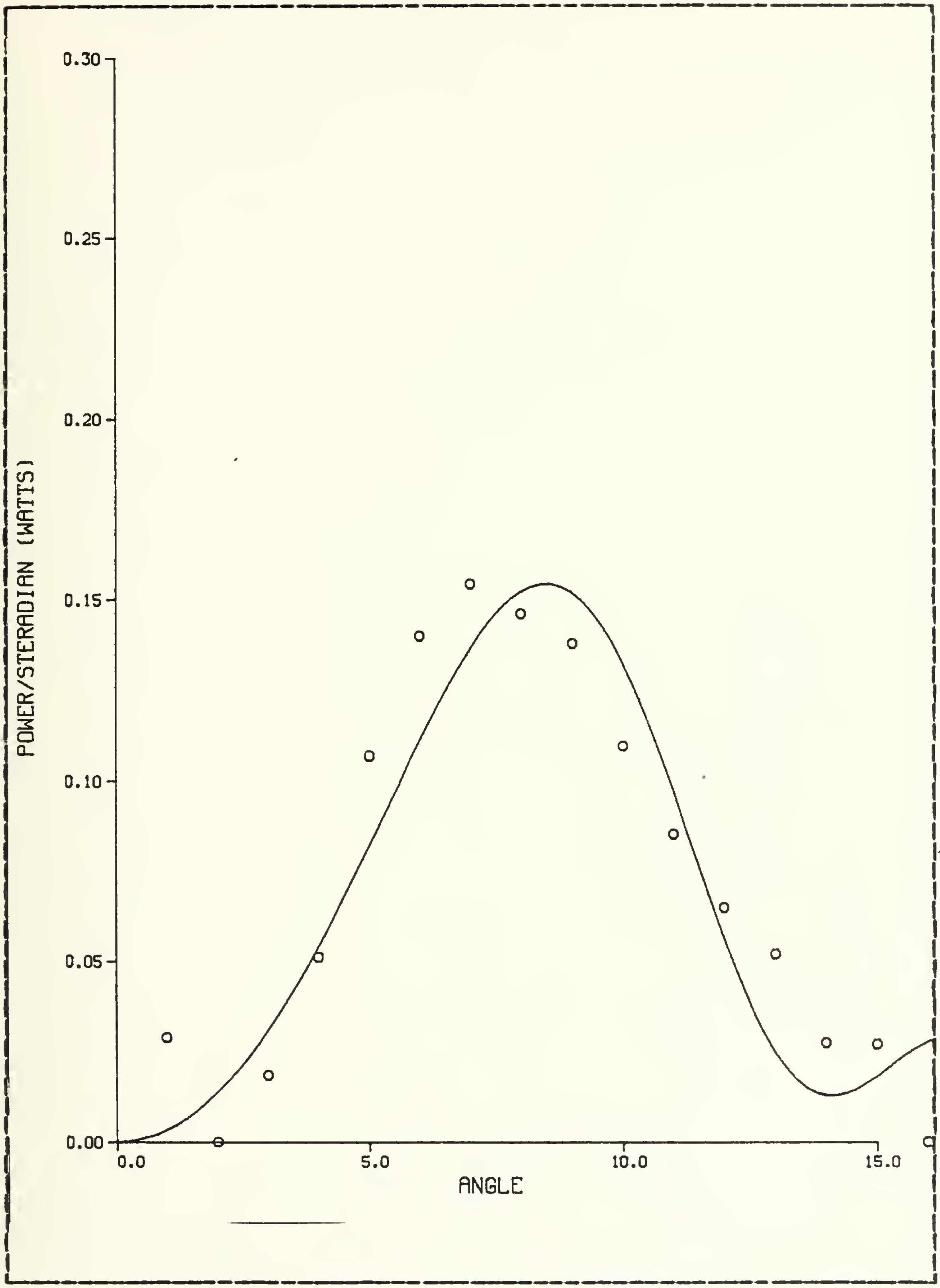

Figure 3.4 Harmonics= 3 + 4 : L=1.0 m : Filter = Waveguide.

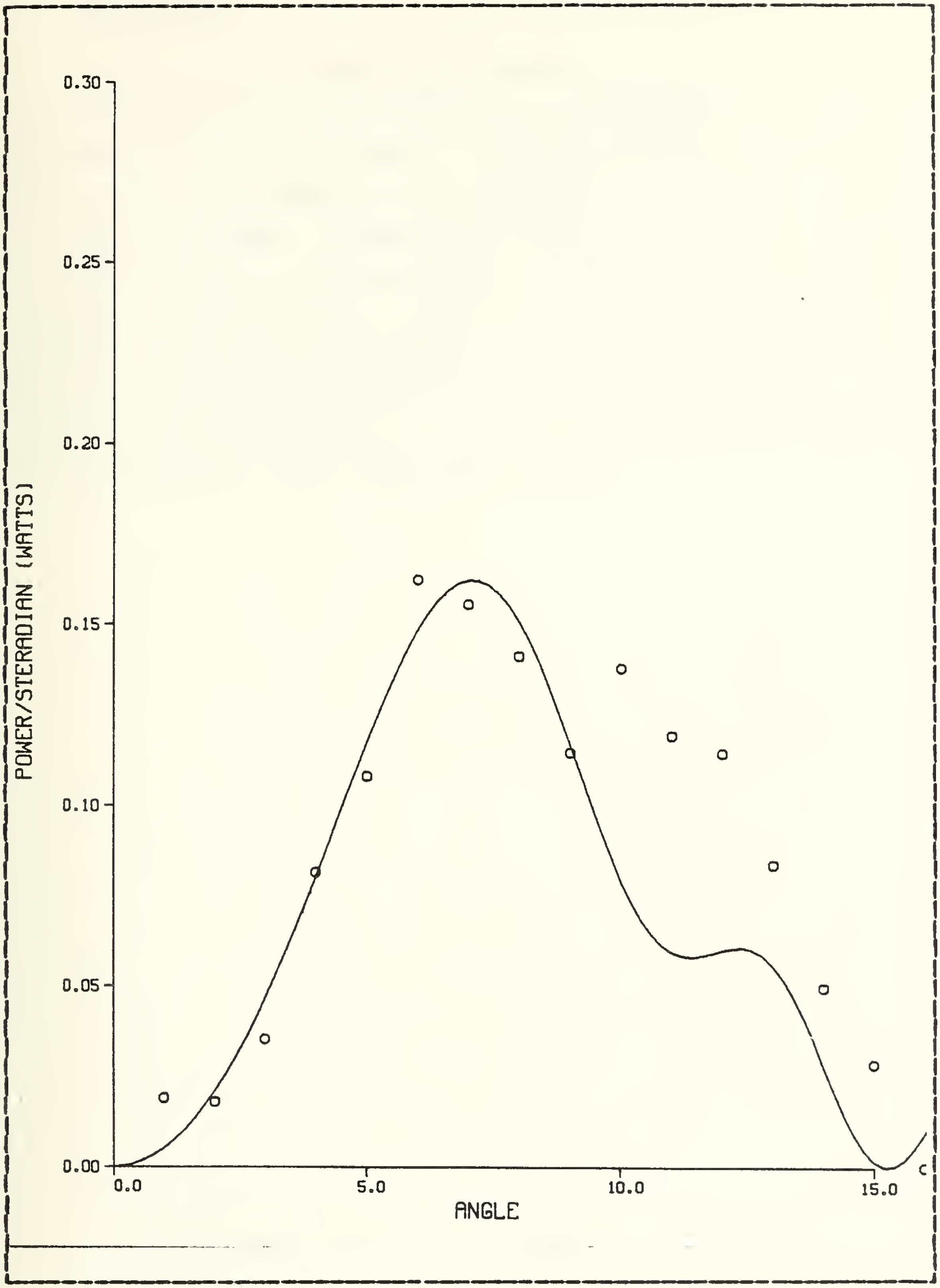

Figure 3.5 Harmonics= 3 + 6 : L=1.0 m : Filter = 3rd.

C. CONCLUSIONS

The results presented here demonstrate initial confirmation of the theory. Although it is difficult to improve the geometry of the experiment, definite improvements can be made in the measurement of the microwave radiation. Instead of using waveguide filters and a crystal detector (the use of which leads to measurement ambiguities for harmonics greater than the fourth), a tunable YIG filter coupled to a spectrum analyzer of appropriate sensitivity should be used. This will enable the observer to isolate harmonics for measurement without ambiguity, as well as allowing the measurement of absolute (vice relative) power.

APPENDIX A

FORTRAN PROGRAM FOR CALCULATING CERENKOV RADIATION CURVES

This is an interactive program which calculates and plots Cerenkov radiation curves for the case of a finite path length. Up to five different harmonics of the electron bunch frequency and five different lengths of emission path may be selected for presentation. The program also allows for adjustment of all basic parameters and constants of the Cerenkov power equation. A different curve will be plotted for each distinct combination of path length and harmonic.

```
C     THIS PROGRAM CALCULATES AND PLOTS CERENKOV RADIATION CURVES.  UP TO
C     FIVE HARMONICS AND FIVE LENGTHS OF EMISSION REGION MAY BE CHOSEN.
C     A DIFFERENT CURVE WILL BE PLOTTED FOR EACH DISTINCT COMBINATION OF
C     LENGTH AND HARMONIC.
C
       REAL N, MU, KAY, MO, NUO, IF,B,C,GAMMA,BETA,V,COSTC,
     *                 C1,U,F,CO,N,MU,NUO,Q,E,MO,B
       DIMENSION W(1000), THETA(1000), HARM(5), CELL (5)
C
C      INITIALIZE CONSTANTS
       DATA ICO/'CO  '/,IN/'N   '/,IMU/'MU  '/,INUO/'NUO '/,
     *      IQ/'Q   '/,IE/'E   '/,IMO/'MO  '/,IB/'B   '/,IY/'Y'/,INO/'N'/
           NPOINT = 101
           THETAF = 20.0
           PI = 3.1415926535 9
           DGTORD = 0.0174532925199
           RDTODG = 57.2957795130 8
C
C      *** INITIALIZE PROGRAM CONSTANTS
           CO   =   2.997925E08
           N    =   1.000268E00
           MU   =   1.256E-06
           NUO  =   2.85E09
           Q    =   1.94E-12
           E    =   1.6E-11
           MO   =   9.10953E-31
           B    =   .0024E00
C
C      *** ARE PROGRAM CONSTANTS OK?
 10        WRITE(6,900) CO,N,MU,NUO,Q,E,MO,B
           READ(5,901) IANS
           IF (IANS.EQ.INO) GO TO 40
C      *** NO, PROGRAM CONSTANTS NEED TO BE CHANGED
           WRITE(6,902)
           READ(5,903) IANS
C
           IF(IANS.NE.ICO) GO TO 11
              WRITE(6,904) IANS
              READ(5,*) CO
              GO TO 10
C
 11        IF(IANS.NE.IN) GO TO 12
              WRITE (6,904) IANS
              READ (5,*) N
              GO TO 10
C
 12        IF(IANS.NE.IMU) GO TO 13
              WRITE (6,904) IANS
```

```
      READ  (5,*) MU
      GO TO 10
C
13       IF(IANS.NE.INUO) GO TO 14
      WRITE (6,904) IANS
      READ (5,*) NUO
      GO TO 10
C
14       IF(IANS.NE.IQ) GO TO 15
      WRITE (6,904) IANS
      READ (5,*) C
      GO TO 10
C
15       IF(IANS.NE.IE) GO TO 16
      WRITE (6,904) IANS
      READ (5,*) E
      GO TO 10
C
16       IF(IANS.NE.IMO) GO TO 17
      WRITE (6,904) IANS
      READ (5,*) MO
      GO TO 10
C
17       IF(IANS.NE.IB) GO TO 18
      WRITE (6,904) IANS
      READ (5,*) B
      GO TO 10
C
C        *** ERROR
18        WRITE(6,910)
          GO TO 10
C
40    WRITE(6,905)
      READ(5,*) HARM(1),HARM(2),HARM(3),HARM(4),HARM(5)
      WRITE(6,906)
      READ(5,*) CELL(1),CELL(2),CELL(3),CELL(4),CELL(5)
C
C     CALL TEK618
C     CALL PTEKAL
C     CALL PRTPLT(72,6)
C     CALL VRSTEC(0,0,0)
      CALL COMPRS
C
C     CALL NOBRDR
      CALL PAGE(8.5,11.0)
C
C  THE LOCATION OF THE ORIGIN:
      CALL PHYSOR(1.0,1.0)
```

```
C
C   THE AREA IN INCHES BY INCHES:
        CALL AREA2D(7.0,10.0)
C
C   WHATEVER LABELS DESIRED ON X AND Y AXIS:
        CALL XNAME ('ANGLE $',100)
        CALL YNAME ('POWER/STERADIAN (WATTS) $',100)
        CALL YAXANG(0)
C
C   WHATEVER HEADING DESIRED FOR GRAPH:
        CALL HEADIN('THIS IS A HEADING$',100,1.2,2)
        CALL HEADIN('HEADING ON NEXT LINE$',100,1.2,2)
C
C
C   RANGE AND INCREMENTS OF X AND RANGE AND INCREMENTS OF Y
        CALL GRAF (0.0, 5.0,15.0, 0.0, .01,0.15)
C
C
C   NEED SPLINE FOR SMOOTH FIT (OTHERWISE GET LINEAR FIT)
C       CALL SPLINE
 45     DO 70 J = 1,5
            IF (HARM(J).EQ.0) GO TO 70
C
 50         DO 75 K = 1,5
                IF (CELL(K).EQ.0) GO TO 70
C
C          ***  BEGIN CALCULATIONS
                C = CO / N
                GAMMA = E / (MO*CO*CO)
                BETA = (1.0 - 1.0 / (GAMMA*GAMMA) ) ** 0.5
                V = BETA * CO
                COSTC  = C / V
                C1 = MU*C*NUC*NUO*Q*Q / (8.0*PI*PI)
                KAY = 2.0*PI*HARM(J)*NUO / C
C
                WRITE(50,*) KAY,COSTC,HARM(J), CELL(K)
C
C          ***  CALCULATE FUNCTIONAL VALUES
                RADF = THETAF * DGTORD
                XPOINT =  FLOAT(NPOINT-1)
                DO 80 I=1,NPOINT
                  RATIO = FLOAT(I-1) / XPOINT
                  ANGLE = RATIO * RADF
                  THETA(I) = RATIO * THETAF
                  F = 1/(EXP(0.25 * B*KAY*COS(ANGLE) * B*KAY*COS(ANGLE) ))
                  U =(KAY * CELL(K) * (COSTC-COS(ANGLE)))/2
                  IF = SIN(U) / U
                  W(I) =  C1 * (F*KAY*CELL(K)*SIN(ANGLE)*IF) **2
C
```

```
            WRITE(50,*) W(I),THETA(I),F,IF                              CER01450
C                                                                       CER01460
 80         CONTINUE                                                    CER01470
C                                                                       CER01480
C   CALL CURVE FOR EACH CURVE DESIRED (0 IN LAST PARAMETER              CER01490
C   INDICATES DO NOT DISPLAY DATA POINTS, 1 MEANS DISPLAY               CER01500
C   EVERY DATA POINT)                                                   CER01510
      CALL CURVE (THETA,W,NPOINT,0)                                     CER01520
C     CALL CURVE (X,Y,N,0)                                              CER01530
C     CALL CURVE (X,YY,N,0)                                             CER01540
C                                                                       CER01550
 75       CONTINUE                                                      CER01560
C                                                                       CER01570
 70   CONTINUE                                                          CER01580
C                                                                       CER01590
C                                                                       CER01600
C                                                                       CER01610
      CALL ENDPL(0)                                                     CER01620
C                                                                       CER01630
C     ** USER WANT ANOTHER RUN?                                         CER01640
         WRITE(6,908)                                                   CER01650
         READ(5,901) IANS                                               CER01660
         IF(IANS.EQ.IY) GO TO 10                                        CER01670
      CALL DONEPL                                                       CER01680
 90   CONTINUE                                                          CER01690
      STOP                                                              CER01700
C                                                                       CER01710
 900  FORMAT(/,' PROGRAM CONSTANTS CURRENTLY HAVE VALUES AS FOLLOWS:',/ CER01720
     * ,5X,'CC  =  SPEED OF LIGHT IN VACUUM      =',E14.7,/             CER01730
     * ,5X,'N   =  AIR REFRACTIVE INDEX          =',E14.7,/             CER01740
     * ,5X,'MU  =  PERMEABILITY OF AIR           =',E14.7,/             CER01750
     * ,5X,'NUO =  BUNCH FREQUENCY               =',E14.7,/             CER01760
     * ,5X,'Q   =  ELECTRON CHARGE               =',E14.7,/             CER01770
     * ,5X,'E   =  ELECTRON ENERGY               =',E14.7,/             CER01780
     * ,5X,'MC  =  ELECTRON REST MASS            =',E14.7,/             CER01790
     * ,5X,'B   =  BUNCH SIZE PARAMETER          =',E14.7,//            CER01800
     * ' DO YOU WANT TO CHANGE ANY OF THESE VALUES? ( Y OR N )')        CER01810
 901  FORMAT(A1)                                                        CER01820
 902  FORMAT(/,' ENTER CONSTANT TO BE CHANGED:')                        CER01830
 903  FORMAT(A4)                                                        CER01840
 904  FORMAT(' ENTER NEW VALUE FOR ',A4,':')                            CER01850
 905  FORMAT(' ENTER VALUES FOR HARM (HARMONIC OF BUNCH FREQUENCY):')   CER01860
 906  FORMAT(' ENTER VALUES FOR CELL (LENGTH OF EMISSION REGION):')     CER01870
 908  FORMAT(' WANT ANOTHER RUN? ( ENTER Y OR N )')                     CER01880
 910  FORMAT(' THE VARIABLE SELECTED IS NOT IN THE LIST - TRY AGAIN')   CER01890
      END                                                               CER01900
```

APPENDIX B

FORTRAN PROGRAM - CERENKOV CURVES WITH DATA POINTS

This is an interactive program which calculates and plots several Cerenkov radiation curves as well as a single set of experimentally observed data points. Up to five different harmonics of the bunch frequency and five different lengths of the emission path may be chosen for presentation. A different curve will be plotted for each distinct combination of path length and harmonic. The program also allows adjustment of all basic parameters and constants of the Cerenkov power equation. The program then prompts for 20 data measurements of power (one per degree) which will be superimposed over the curves.

```
C     THIS PROGRAM CALCULATES AND PLOTS CERENKOV RADIATION CURVES FOR
C     UP TO FIVE DIFFERENT HARMONICS AND FIVE DIFFERENT LENGTHS OF
C     EMISSION REGION.  A DIFFERENT CURVE WILL BE CALCULATED FOR EACH
C     DISTINCT COMBINATION OF LENGTH AND HARMONIC.  THE PROGRAM THEN ASKS
C     FOR 20 DATA POINTS (ONE PER DEGREE) TO BE SUPERIMPOSED OVER THE
C     CURVES.
C
        REAL N, MU, KAY, MO, NUO, IF,B,C,GAMMA,BETA,V,COSTC,
       *              C1,U,F,CO,N,MU,NUO,Q,E,MO,B
        DIMENSION W(1000), THETA(1000), HARM(5), CELL (5), THETAP(20),
       *          POWER(20)
C
C       INITIALIZE CONSTANTS
        DATA ICO/'CO  '/,IN/'N   '/,IMU/'MU  '/,INUO/'NUO '/,
       *     IQ/'Q   '/,IE/'E   '/,IMO/'MO  '/,IB/'B   '/,IY/'Y'/,INO/'N'/
            NPOINT = 101
            THETAF = 20.0
            PI = 3.14159265359
            DGTORD = 0.0174532925199
            RDTODG = 57.2957795130 8
C
C       *** INITIALIZE PROGRAM CONSTANTS
            CO   =  2.997925E08
            N    =  1.000268E00
            MU   =  1.256E-06
            NUO  =  2.85E09
            Q    =  1.94E-12
            E    =  1.6E-11
            MO   =  9.10953E-31
            B    =  .0024E00
C
C       *** ARE PROGRAM CONSTANTS OK?
 10         WRITE(6,900) CO,N,MU,NUO,Q,E,MO,B
            READ(5,901) IANS
            IF (IANS.EQ.INO) GO TO 40
C       *** NO, PROGRAM CONSTANTS NEED TO BE CHANGED
            WRITE(6,902)
            READ(5,903) IANS
C
            IF(IANS.NE.ICO) GO TO 11
               WRITE(6,904) IANS
               READ(5,*) CO
               GO TO 10
C
 11         IF(IANS.NE.IN) GO TO 12
               WRITE (6,904) IANS
               READ (5,*) N
               GO TO 10
```

```
C
12        IF(IANS.NE.IMU) GO TO 13
             WRITE (6,904) IANS
             READ  (5,*) MU
             GO TO 10
C
13        IF(IANS.NE.INUO) GO TO 14
             WRITE (6,904) IANS
             READ (5,*) NUO
             GO TO 10
C
14        IF(IANS.NE.IQ) GO TO 15
             WRITE (6,904) IANS
             READ (5,*) Q
             GO TO 10
C
15        IF(IANS.NE.IE) GO TO 16
             WRITE (6,904) IANS
             READ (5,*) E
             GO TO 10
C
16        IF(IANS.NE.IMO) GO TO 17
             WRITE (6,904) IANS
             READ (5,*) MO
             GO TO 10
C
17        IF(IANS.NE.IB) GO TO 18
             WRITE (6,904) IANS
             READ (5,*) B
             GO TO 10
C
C         *** ERROR
18            WRITE(6,910)
              GO TO 10
C
40    WRITE(6,905)
      READ(5,*) HARM(1),HARM(2),HARM(3),HARM(4),HARM(5)
      WRITE(6,906)
      READ(5,*) CELL(1),CELL(2),CELL(3),CELL(4),CELL(5)
C
      WRITE(6,907)
      DO 41 I = 1,20
            READ(5,*) POWER(I)
41    CONTINUE
C
      DO 42 I = 1,20
            THETAP(I) = I
42    CONTINUE
```

```
C                                                                       CER00970
C                                                                       CER00980
C     CALL TEK618                                                       CER00990
C     CALL PTEKAL                                                       CER01000
C     CALL PRTPLT(72,6)                                                 CER01010
C     CALL VRSTEC(0,0,0)                                                CER01020
      CALL COMPRS                                                       CER01030
C                                                                       CER01040
C     CALL NOBRDR                                                       CER01050
      CALL PAGE(8.5,11.0)                                               CER01060
C                                                                       CER01070
C  THE LOCATION OF THE ORIGIN:                                          CER01080
C     CALL PHYSOR(1.0,1.0)                                              CER01090
C                                                                       CER01100
C  THE AREA IN INCHES BY INCHES:                                        CER01110
      CALL AREA2D(7.0,10.0)                                             CER01120
C                                                                       CER01130
C  WHATEVER LABELS DESIRED ON X AND Y AXIS:                             CER01140
      CALL XNAME ('ANGLE $',100)                                        CER01150
      CALL YAXANG(0)                                                    CER01160
      CALL YNAME ('POWER/STERADIAN (WATTS) $',100)                      CER01170
C                                                                       CER01180
C  WHATEVER HEADING DESIRED FOR GRAPH:                                  CER01190
C     CALL HEADIN('THIS IS A HEADING$',100,1.2,2)                       CER01200
C     CALL HEADIN('HEADING ON NEXT LINE$',100,1.2,2)                    CER01210
C                                                                       CER01220
C  RANGE AND INCREMENTS OF X AND RANGE AND INCREMENTS OF Y              CER01230
      CALL GRAF (0.0, 5.0,15.0, 0.0, .01,0.15)                          CER01240
C                                                                       CER01250
C                                                                       CER01260
C  NEED SPLINE FOR SMOOTH FIT (OTHERWISE GET LINEAR FIT)                CER01270
C     CALL SPLINE                                                       CER01280
 45   DO 70 J = 1,5                                                     CER01290
         IF (HARM(J).EQ.0) GO TO 70                                     CER01300
C                                                                       CER01310
 50      DO 75 K = 1,5                                                  CER01320
            IF (CELL(K).EQ.0) GO TO 70                                  CER01330
C                                                                       CER01340
C       *** BEGIN CALCULATIONS                                          CER01350
            C = CO / N                                                  CER01360
            GAMMA = E / (MO*CO*CO)                                      CER01370
            BETA = (1.0 - 1.0 / (GAMMA*GAMMA) ) ** 0.5                  CER01380
            V = BETA * CO                                               CER01390
            COSTC  = C / V                                              CER01400
            C1 = MU*C*NUC*NUO*Q*Q / (8.0*PI*PI)                         CER01410
            KAY = 2.0*PI*HARM(J)*NUO / C                                CER01420
C                                                                       CER01430
            WRITE(50,*) KAY,COSTC,HARM(J), CELL(K)                      CER01440
```

```
C
C        *** CALCULATE FUNCTIONAL VALUES
             RADF = THETAF * DGTORD
             XPOINT = FLOAT(NPOINT-1)
             DO 80 I=1,NPOINT
                RATIO = FLOAT(I-1) / XPOINT
                ANGLE = RATIO * RADF
                THETA(I) = RATIO * THETAF
                F = 1/(EXP(0.25 * B*KAY*COS(ANGLE) * B*KAY*COS(ANGLE) ))
                U =(KAY * CELL(K) * (COSTC-COS(ANGLE)))/2
                IF = SIN(U) / U
                W(I) =  C1  * (F*KAY*CELL(K)*SIN(ANGLE)*IF)**2
C
                WRITE(50,*) W(I),THETA(I),F,IF
C
 80             CONTINUE
C
C  CALL CURVE FOR EACH CURVE DESIRED (0 IN LAST PARAMETER
C  INDICATES DO NOT DISPLAY DATA POINTS, 1 MEANS DISPLAY
C  EVERY DATA POINT)
         CALL CURVE (THETA,W,NPOINT,0)
C        CALL CURVE (X,Y,N,0)
C        CALL CURVE (X,YY,N,0)
C
 75          CONTINUE
C
 70      CONTINUE
C
         CALL CURVE (THETAP,POWER,20,-1)
C
         CALL ENDPL(0)
C
C        ** USER WANT ANOTHER RUN?
            WRITE(6,908)
            READ(5,901) IANS
            IF(IANS.EQ.IY) GO TO 10
         CALL DONEPL
 90      CONTINUE
         STOP
C
 900     FORMAT(/,' PROGRAM CONSTANTS CURRENTLY HAVE VALUES AS FOLLOWS:',/
        * ,5X,'CC  =  SPEED OF LIGHT IN VACUUM      =',E14.7,/
        * ,5X,'N   =  AIR REFRACTIVE INDEX          =',E14.7,/
        * ,5X,'ML  =  PERMEABILITY OF AIR           =',E14.7,/
        * ,5X,'NLO =  BUNCH FREQUENCY               =',E14.7,/
        * ,5X,'C   =  ELECTRON CHARGE               =',E14.7,/
        * ,5X,'E   =  ELECTRON ENERGY               =',E14.7,/
        * ,5X,'MC  =  ELECTRON REST MASS            =',E14.7,/
```

```
     * ,5X,'B    =  BUNCH SIZE PARAMETER              =',E14.7,//           CER01930
     * ' DO YOU WANT TO CHANGE ANY OF THESE VALUES? ( Y OR N )')            CER01940
 901  FORMAT(A1)                                                            CER01950
 902  FORMAT(/,' ENTER CONSTANT TO BE CHANGED:')                            CER01960
 903  FORMAT(A4)                                                            CER01970
 904  FORMAT(' ENTER NEW VALUE FOR ',A4,':')                                CER01980
 905  FORMAT(' ENTER VALUES FOR HARM (HARMONIC OF BUNCH FREQUENCY):')       CER01990
 906  FORMAT(' ENTER VALUES FOR CELL (LENGTH OF EMISSION REGION):')         CER02000
 907  FORMAT(' ENTER EXPERIMENTAL VALUES FOR POWER:')                       CER02010
 908  FORMAT(' WANT ANOTHER RUN? ( ENTER Y OR N )')                         CER02020
 910  FORMAT(' THE VARIABLE SELECTED IS NOT IN THE LIST - TRY AGAIN')       CER02030
      END                                                                   CER02040
```

APPENDIX C

FORTRAN PROGRAM - SUM OF CERENKOV CURVES WITH DATA POINTS

This is an interactive program which calculates and plots a single Cerenkov radiation curve and superimposes a single set of data points over the curve. The single Cerenkov curve will represent a sum of curves. The sum will be composed of each distinct combination of harmonic and path length chosen. Up to five different lengths of emission path and five different harmonics of the bunch frequency may be chosen. The program also allows adjustment of all basic parameters and constants of the Cerenkov power equation. The program will prompt for 20 data measurements of power (one for each degree of angle).

```
C     THIS PROGRAM CALCULATES AND PLOTS A SUM OF CERENKOV RADIATION
C     CURVES.  UP TO FIVE HARMONICS AND FIVE LENGTHS OF EMISSION REGION
C     MAY BE CHCSEN; THE PROGRAM WILL INCLUDE A DIFFERENT CURVE IN THE SUM
C     FOR EACH DISTINCT COMBINATION OF LENGTH AND HARMONIC.  THE PRCGRAM
C     THEN ASKS FOR 20 CATA PCINTS (ONE PER DEGREE) TO BE SUPERIMPOSED
C     CVER THE CURVE.
C
        REAL N, MU, KAY, MO, NUO, IF,B,C,GAMMA,BETA,V,COSTC,
       *              C1,U,F,CO,N,MU,NUO,Q,E,MO,B
        DIMENSICN W(1000), THETA(1000), HARM(5), CELL (5), THETAP(20),
       *          PCWER(20), SUM(1000)
C
C       INITIALIZE CONSTANTS
        DATA ICC/'CO  '/,IN/'N   '/,IMU/'MU  '/,INUO/'NUO '/,
       *     IQ/'Q   '/,IE/'E   '/,IMO/'MO  '/,IB/'B   '/,IY/'Y'/,INO/'N'/
           NPCINT = 101
           THETAF = 20.0
           PI = 3.14159265359
           DGTCRD = 0.0174532925199
           RDTCDG = 57.2957795130 8
C
C       *** INITIALIZE PROGRAM CONSTANTS
           CO   =  2.997925E08
           N    =  1.000268E00
           MU   =  1.256E-06
           NUC  =  2.85E09
           Q    =  1.94E-12
           E    =  1.6E-11
           MO   =  9.10953E-31
           B    =  .0024E00
C
C       *** ARE PROGRAM CONSTANTS CK?
 10        WRITE(6,900) CO,N,MU,NUO,Q,E,MO,B
           READ(5,901) IANS
           IF (IANS.EQ.INC) GC TO 40
C       *** NO, PROGRAM CONSTANTS NEED TO BE CHANGEC
           WRITE(6,902)
           READ(5,903) IANS
C
           IF(IANS.NE.ICO) GO TO 11
              WRITE(6,904) IANS
              READ(5,*) CO
              GC TC 10
C
 11        IF(IANS.NE.IN) GO TO 12
              WRITE (6,904) IANS
              READ (5,*) N
              GC TC 10
```

```
C
 12        IF(IANS.NE.IMU) GO TO 13
              WRITE (6,904) IANS
              READ  (5,*) MU
              GO TO 10
C
 13        IF(IANS.NE.INUO) GO TO 14
              WRITE (6,904) IANS
              READ (5,*) NUO
              GO TO 10
C
 14        IF(IANS.NE.IQ) GO TO 15
              WRITE (6,904) IANS
              READ (5,*) C
              GO TO 10
C
 15        IF(IANS.NE.IE) GO TO 16
              WRITE (6,904) IANS
              READ (5,*) E
              GO TO 10
C
 16        IF(IANS.NE.IMO) GO TO 17
              WRITE (6,904) IANS
              READ (5,*) MO
              GO TO 10
C
 17        IF(IANS.NE.IB) GO TO 18
              WRITE (6,904) IANS
              READ (5,*) B
              GO TO 10
C
C          *** ERROR
 18           WRITE(6,910)
              GO TO 10
C
 40     WRITE(6,905)
        READ(5,*) HARM(1),HARM(2),HARM(3),HARM(4),HARM(5)
        WRITE(6,906)
        READ(5,*) CELL(1),CELL(2),CELL(3),CELL(4),CELL(5)
C
        WRITE(6,907)
        DO 41  I = 1,20
              READ(5,*) POWER(I)
 41     CONTINUE
C
        DO 42  I = 1,20
              THETAP(I) = I
 42     CONTINUE
```

```
C                                                                       SUMO0970
C                                                                       SUMO0980
C     CALL TEK618                                                       SUMO0990
C     CALL PTEKAL                                                       SUMO1000
C     CALL PRTPLT(72,6)                                                 SUMO1010
C     CALL VRSTEC(0,0,0)                                                SUMO1020
      CALL CCMPRS                                                       SUMO1030
C     CALL NOBRDR                                                       SUMO1040
      CALL PAGE(8.5,11.0)                                               SUMO1050
C                                                                       SUMO1060
C  THE LOCATION OF THE ORIGIN:                                          SUMO1070
C     CALL PHYSOR(1.0,1.0)                                              SUMO1080
C                                                                       SUMO1090
C  THE AREA IN INCHES BY INCHES:                                        SUMO1100
      CALL AREA2D(7.0,10.0)                                             SUMO1110
C                                                                       SUMO1120
C  WHATEVER LABELS DESIRED ON X AND Y AXIS:                             SUMO1130
      CALL XNAME ('ANGLE $',100)                                        SUMO1140
      CALL YNAME ('POWER/STERADIAN (WATTS) $',100)                      SUMO1150
      CALL YAXANG (0)                                                   SUMO1160
C                                                                       SUMO1170
C  WHATEVER HEADING DESIRED FOR GRAPH:                                  SUMO1180
C     CALL HEADIN('THIS IS A HEADING$',100,1.2,2)                       SUMO1190
C     CALL HEADIN('HEADING ON NEXT LINE$',100,1.2,2)                    SUMO1200
C                                                                       SUMO1210
C  RANGE AND INCREMENTS OF X AND RANGE AND INCREMENTS OF Y              SUMO1220
      CALL GRAF (0.0, 5.0,15.0, 0.0,0.05,0.30)                          SUMO1230
C                                                                       SUMO1240
C                                                                       SUMO1250
C  NEED SPLINE FOR SMOOTH FIT (OTHERWISE GET LINEAR FIT)                SUMO1260
C     CALL SPLINE                                                       SUMO1270
C                                                                       SUMO1280
      DO 69 I = 1,NPOINT                                                SUMO1290
         SUM(I) = 0                                                     SUMO1300
 69   CONTINUE                                                          SUMO1310
C                                                                       SUMO1320
 45   DO 70 J = 1,5                                                     SUMO1330
         IF (HARM(J).EQ.0) GO TO 70                                     SUMO1340
C                                                                       SUMO1350
 50      DO 75 K = 1,5                                                  SUMO1360
            IF (CELL(K).EQ.0) GO TO 70                                  SUMO1370
C                                                                       SUMO1380
C          *** BEGIN CALCULATIONS                                       SUMO1390
            C = CO / N                                                  SUMO1400
            GAMMA = E / (MO*CO*CO)                                      SUMO1410
            BETA = (1.0 - 1.0 / (GAMMA*GAMMA) ) ** 0.5                  SUMO1420
            V = BETA * CO                                               SUMO1430
            COSTC  = C / V                                              SUMO1440
```

```
          C1 = MU*C*NUO*NUO*Q*C / (8.0*PI*PI)                          SUM01450
          KAY = 2.0*PI*HARM(J)*NUO / C                                 SUM01460
C                                                                      SUM01470
          WRITE(50,*) KAY,COSTC,HARM(J), CELL(K)                       SUM01480
C                                                                      SUM01490
C     *** CALCULATE FUNCTIONAL VALUES                                  SUM01500
          RADF = THETAF * DGTORD                                       SUM01510
          XPOINT = FLOAT(NPOINT-1)                                     SUM01520
          DO 80 I=1,NPOINT                                             SUM01530
            RATIO = FLOAT(I-1) / XPOINT                                SUM01540
            ANGLE = RATIO * RADF                                       SUM01550
            THETA(I) = RATIO * THETAF                                  SUM01560
            F = 1/(EXP(0.25 * B*KAY*COS(ANGLE) * B*KAY*COS(ANGLE) ))   SUM01570
            U =(KAY * CELL(K) * (COSTC-COS(ANGLE)))/2                  SUM01580
            IF = SIN(U) / U                                            SUM01590
            W(I) =  C1 * (F*KAY*CELL(K)*SIN(ANGLE)*IF)**2              SUM01600
            SUM(I) = W(I) + SUM(I)                                     SUM01610
            WRITE(50,*) SUM(I),THETA(I)                                SUM01620
C                                                                      SUM01630
C           WRITE(50,*) W(I),THETA(I),F,IF                             SUM01640
C                                                                      SUM01650
 80         CONTINUE                                                   SUM01660
C                                                                      SUM01670
C  CALL CURVE FOR EACH CURVE DESIRED (0 IN LAST PARAMETER              SUM01680
C  INDICATES DO NOT DISPLAY DATA POINTS, 1 MEANS DISPLAY               SUM01690
C  EVERY DATA POINT)                                                   SUM01700
C       CALL CURVE (THETA,W,NPOINT,0)                                  SUM01710
C       CALL CURVE (X,Y,N,0)                                           SUM01720
C       CALL CURVE (X,YY,N,0)                                          SUM01730
C                                                                      SUM01740
 75         CONTINUE                                                   SUM01750
C                                                                      SUM01760
 70     CONTINUE                                                       SUM01770
C                                                                      SUM01780
        CALL CURVE (THETA,SUM,NPOINT,0)                                SUM01790
        CALL CURVE (THETAP,POWER,20,-1)                                SUM01800
C                                                                      SUM01810
        CALL ENDPL(0)                                                  SUM01820
C                                                                      SUM01830
C       ** USER WANT ANOTHER RUN?                                      SUM01840
           WRITE(6,908)                                                SUM01850
           READ(5,901) IANS                                            SUM01860
           IF(IANS.EQ.IY) GO TO 10                                     SUM01870
        CALL DONEPL                                                    SUM01880
 90     CONTINUE                                                       SUM01890
        STOP                                                           SUM01900
C                                                                      SUM01910
 900    FORMAT(/,' PROGRAM CONSTANTS CURRENTLY HAVE VALUES AS FOLLOWS:',/ SUM01920
```

```
     * ,5X,'CC   =  SPEED OF LIGHT IN VACUUM      =',E14.7,/              SUM01930
     * ,5X,'N    =  AIR REFRACTIVE INDEX          =',E14.7,/              SUM01940
     * ,5X,'MU   =  PERMEABILITY OF AIR           =',E14.7,/              SUM01950
     * ,5X,'NUO  =  BUNCH FREQUENCY               =',E14.7,/              SUM01960
     * ,5X,'Q    =  ELECTRON CHARGE               =',E14.7,/              SUM01970
     * ,5X,'E    =  ELECTRON ENERGY               =',E14.7,/              SUM01980
     * ,5X,'MO   =  ELECTRON REST MASS            =',E14.7,/              SUM01990
     * ,5X,'B    =  BUNCH SIZE PARAMETER          =',E14.7,//             SUM02000
     * ' DO YOU WANT TO CHANGE ANY OF THESE VALUES? ( Y OR N )')          SUM02010
 901  FORMAT(A1)                                                          SUM02020
 902  FORMAT(/,' ENTER CONSTANT TO BE CHANGED:')                          SUM02030
 903  FORMAT(A4)                                                          SUM02040
 904  FORMAT(' ENTER NEW VALUE FOR ',A4,':')                              SUM02050
 905  FORMAT(' ENTER VALUES FOR HARM (HARMONIC OF BUNCH FREQUENCY):')     SUM02060
 906  FORMAT(' ENTER VALUES FOR CELL (LENGTH OF EMISSION REGION):')       SUM02070
 907  FORMAT(' ENTER EXPERIMENTAL VALUES FOR POWER:')                     SUM02080
 908  FORMAT(' WANT ANOTHER RUN? ( ENTER Y OR N )')                       SUM02090
 910  FORMAT(' THE VARIABLE SELECTED IS NOT IN THE LIST - TRY AGAIN')     SUM02100
      END                                                                 SUM02110
```

APPENDIX D
EXPERIMENTAL APPARATUS

This appendix contains photographs of the experimental apparatus used in this experiment. Figure D.1 shows the end station of the LINAC. At the right is the LINAC beam aperture, with the reflecting aluminum mirror at the left. The detector assembly, mounted at the end of the pivot arm, is shown in the foreground of the photograph. Also shown, located along the beam path between the aperture and the mirror, is a small portable laser used to align the mirror.

Figure D.2 shows the waveguide filter with the fin-line insert for one of the harmonics, along with the detector and horn. Figure D.3 shows the detector apparatus assembled.

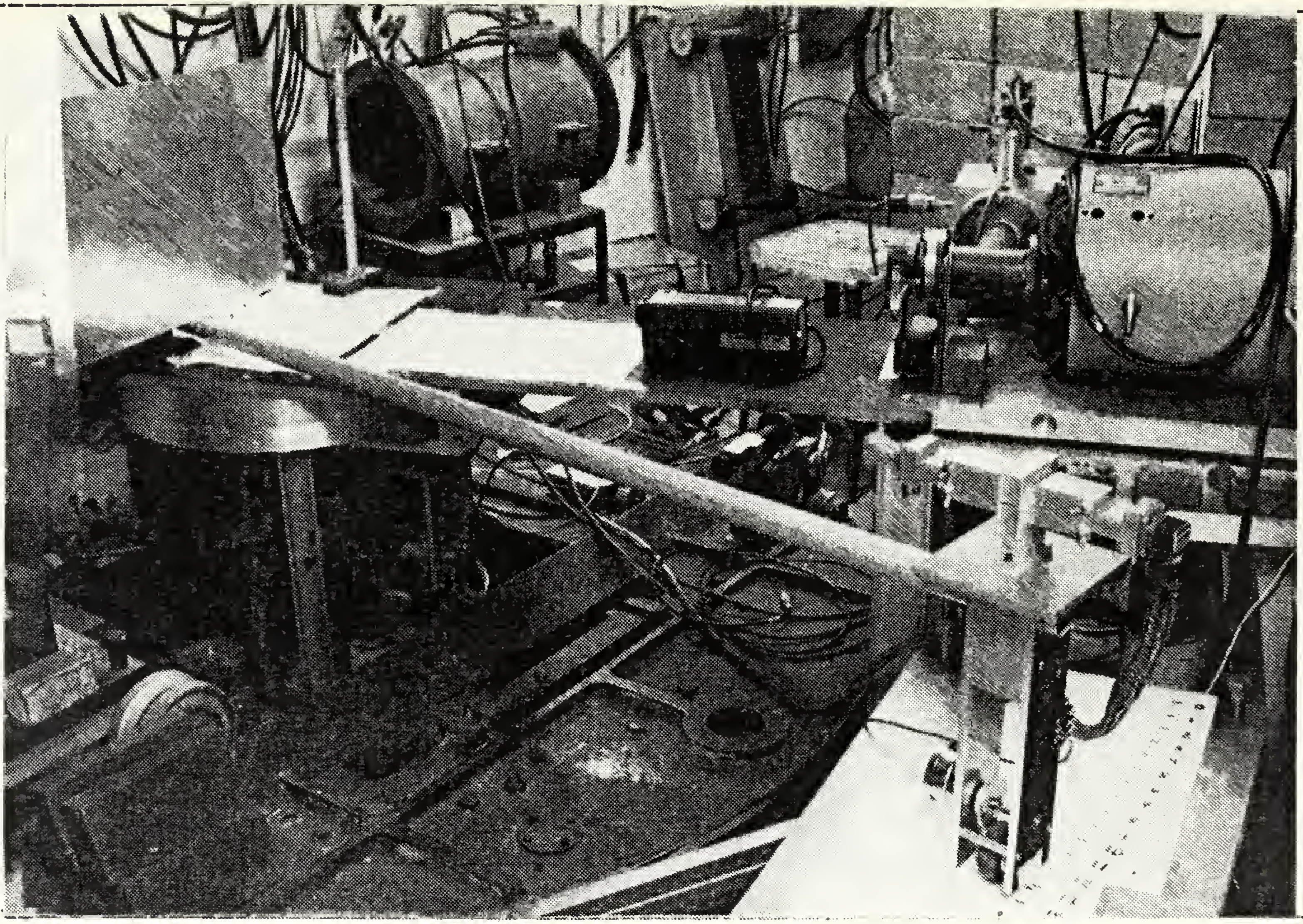

Figure D.1 LINAC End-Station.

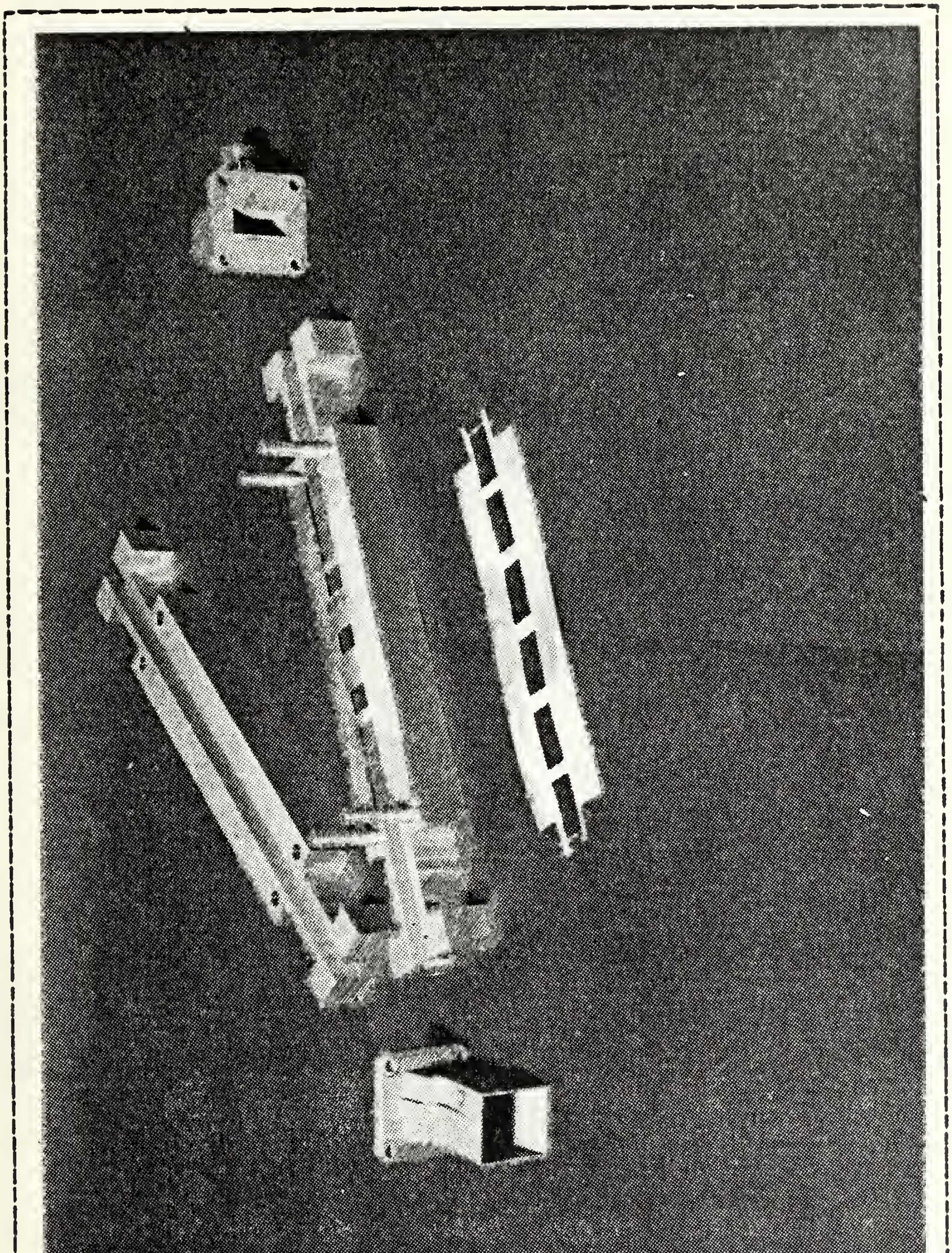

Figure D.2 Detection Apparatus Components.

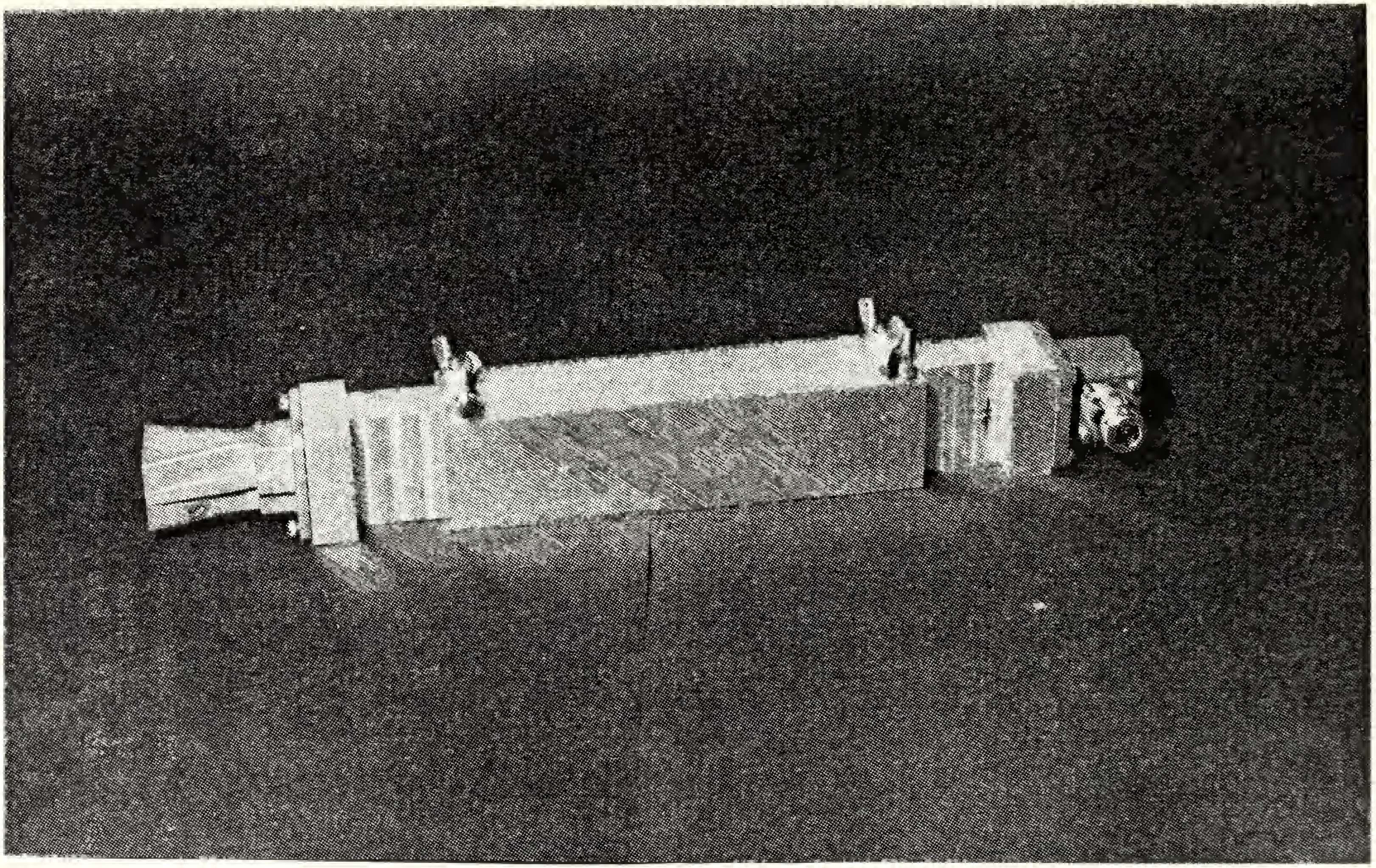

Figure D.3 Assembled Detection Apparatus.

APPENDIX E

TABULAR DATA FOR FIGURES

TABLE III

Tabular Data for Figure 3.1

Degree	Channel	Normalized Value
1	101	.0082
2	96	.0078
3	188	.0153
4	434	.0352
5	575	.0467
6	864	.0701
7	828	.0672
8	752	.0610
9	610	.0495
10	734	.0596
11	635	.0515
12	609	.0494
13	446	.0362
14	265	.0215
15	152	.0123

-Channel values were read from the Pulse Height Analyzer

-Normalizing factor was 8.1134E-05

-Beam current = 4.0E-08 Amps

TABLE IV

Tabular Data for Figure 3.2

Degree	Channel	Normalized Value
1	219	.0244
2	114	.0127
3	198	.0221
4	284	.0317
5	556	.0620
6	694	.0774
7	772	.0861
8	786	.0877
9	572	.0638
10	393	.0438
11	304	.0339
12	193	.0215
13	190	.0212
14	64	.0071
15	0	.0000

-Channel values were read from Pulse Height Analyzer

-Normalizing factor was 1.1158E-04

-Beam current = 4.0E-08 Amps

TABLE V

Tabular Data for Figure 3.3

Degree	Channel	Normalized Value
1	117	.0837
2	0	.0000
3	75	.0537
4	207	.1481
5	431	.3083
6	565	.4042
7	623	.4457
8	590	.4221
9	556	.3978
10	442	.3162
11	344	.2461
12	262	.1874
13	210	.1502
14	111	.0794
15	109	.0780

-Channel values were read from Pulse Height Analyzer

-Normalizing Factor was 3.9502E-04

-Beam current = 4.0E-08 Amps

TABLE VI

Tabular Data for Figure 3.4

Degree	Channel	Normalized Value
1	117	.0290
2	0	.0000
3	75	.0186
4	207	.0513
5	431	.1069
6	565	.1401
7	623	.1545
8	590	.1463
9	556	.1379
10	442	.1096
11	344	.0853
12	262	.0650
13	210	.0521
14	111	.0275
15	109	.0270

-Channel Values were read from the Pulse Height Analyzer

-Normalizing factor was 2.48E-04

-Beam current = 4.0E-08 Amps

TABLE VII

Tabular Data for Figure 3.5

Degree	Channel	Normalized Value
1	101	.0190
2	96	.0180
3	188	.0353
4	434	.0815
5	575	.1080
6	864	.1623
7	828	.1555
8	752	.1413
9	610	.1146
10	734	.1379
11	635	.1193
12	609	.1144
13	446	.0838
14	265	.0498
15	152	.0286

-Channel values were read from the Pulse Height Analyzer

-Normalizing factor was 1.878E-04

-Beam current = 4.0E-08 Amps

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Thesis
N4692 Newton
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electron bunches in a
finite air path.